N72-12421

NASA CR-72844

DEVELOPMENT OF THE ACTIVATED DIFFUSION BRAZING PROCESS for FABRICATION OF FINNED SHELL TO STRUT TURBINE BLADES

by

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General Electric Company

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA Lewis Research Center

Contract NAS3-12433

Joseph M. Ladd, Project Manager

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Scientific and Technical Information Facility
P.O. Box 33
College Park, Md. 20740

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA CR-72844		

4. Title and Subtitle Development of the Activated Diffusion Brazing Process for Fabrication of Finned Shell to Strut Turbine Blades	5. Report Date November, 1971 6. Performing Organization Code
7. Author(s) L.G. Wilbers, T.F. Berry, R.E. Kutchera, and R.E. Edmonson	8. Performing Organization Report No.
9. Performing Organization Name and Address General Electric Company Aircraft Engine Group Evendale, Ohio 45215	10. Work Unit No. 11. Contract or Grant No. NAS3-12433
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546	13. Type of Report and Period Covered Contract Report 14. Sponsoring Agency Code

15. Supplementary Notes

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16. Abstract

The activated diffusion brazing process was developed for attaching TDNiCr and U700 finned airfoil shells to matching Rene' 80 struts without obstructing the finned cooling passageways. Creep forming the finned shells to struts in combination with precise preplacement of brazing alloy resulted in consistently sound joints, free of cooling passageway clogging. Extensive tensile and stress rupture testing of several joint orientations at several temperatures provided a critical assessment of joint integrity of both material combinations.

Trial blades of each material combination were fabricated followed by destructive metallographic examination which verified high joint integrity. Subsequently, six blades of each material combination were fabricated and delivered to NASA.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Activated Diffusion Brazings, Fabricated Turbine Blade, Finned Shell to Strut Design, U700 or TDNiCr to Rene' 80	Unclassified - unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	158	

* For sale by the National Technical Information Service, Springfield, Virginia 22151

FOREWARD

The research described herein, which was conducted by the General Electric Company, Aircraft Engine Group, was performed under NASA Contract NAS3-12433. The work was done under the management of the NASA Project Manager, Mr. Joseph M. Ladd, Airbreathing Engine Division, NASA-Lewis Research Center. Mr. A. Kaufman and Mr. T. Moore of NASA were Research Advisors on this contract.

ABSTRACT

The activated diffusion brazing process was developed for attaching TDNiCr and U700 finned airfoil shells to matching Rene' 80 struts without obstructing the finned cooling passageways. Creep forming the finned shells to struts in combination with precise preplacement of brazing alloy resulted in consistently sound joints, free of cooling passageway clogging. Extensive tensile and stress rupture testing of several joint orientations at several temperatures provided a critical assessment of joint integrity of both material combinations.

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1.0 SUMMARY

An activated diffusion brazing process was developed for attaching TDNiCr and U700 finned airfoil shells to matching Rene' 80 struts without obstructing the finned cooling passageways or damaging other parts of the blade. The joining development work was concentrated on establishing the feasibility of reliably joining the finned shells to the struts. Other peripheral fabrication (fin matching, shell forming, hole drilling, tip cap attachment, trailing edge sealing, and shell to platform joining) were conducted with minimal development effort.

Extensive tensile and stress rupture testing of several joint orientations at several temperatures provided a critical assessment of joint integrity of both TDNiCr-Rene' 80 and U700 - Rene' 80 combinations. Metallographic examination verified the joint quality and revealed that sound activated diffusion brazed joints could consistently be produced. Generous fillets were formed along the fin to strut juncture, thereby reducing any stress concentration.

Thermal cycling of sufficiently highly restrained TDNiCr finned shell to strut brazements resulted in fin cracking. Judicious selection of design and thermal exposure must be exercised to prevent such cracking. Thermal cycling of the U700 finned shell to strut combination resulted in reduced stress rupture properties. Application of a coating to the U700 combination prevented oxidation but created a weak diffusion zone; consequently, it did not improve properties.

Creep forming the finned shells to struts, in combination with precise preplacement of the brazing alloy, resulted in consistently sound joints, free of cooling passageway clogging. The joining process was shown to be applicable to complex turbine blades with twist, compound curvature, and variable chord width. Trial blades of each material combination were fabricated, followed by destructive metallographic examination, which verified high joint integrity. Subsequently, six blades of each material combination were fabricated and delivered to NASA.

2.0 INTRODUCTION

The continuing evolution of aircraft gas turbines to produce engines with improved thrust-to-weight ratios and specific fuel consumptions has resulted in ever-increasing turbine inlet temperatures, since the thermodynamic efficiency of the engine cycle invariably increases with this critical temperature. These continually increasing turbine inlet temperatures have imposed increasingly stringent requirements on the rotating and stationary components (wheels, blades, and vanes) used in the primary turbine of single spool engines and in the high pressure turbines of multiple spool engines. Initially, these requirements were met by evolutionary improvements in the high temperature strengths of the cobalt and nickel-base alloys used in turbine airfoils and wheels.

Over the past 30 years, 1500°F (1089 K)/100 hr (Reference 1) stress rupture strength has increased nearly seven-fold; but the bulk of this strength improvement had occurred by about 1960. The modern gas turbines of today and foreseeably for the next decade, do and will employ increasingly sophisticated schemes of air-cooling to accommodate the requirements of increasing turbine inlet temperatures. These air-cooling designs are varied depending on factors including engine mission, but often require high strength joints for successful operation. The finned shell to strut design (shown in Figure 1) is representative of advanced designs which require a high strength, reliable joining process for successful fabrication. However, the alloys developed to meet the strength requirements of advanced turbine components are difficult to weld by conventional fusion welding processes because the alloys are subject to both strain-age and hot cracking.

The finned shell to strut design (Figure 1), the fabrication of which is the subject of this report, is a typical example of an advanced air cooled blade (or vane) design which requires a high strength, reliable joining process for successful fabrication. The high temperature resistant alloys selected for this design, Rene' 80 for the strut, TD Nickel Chromium (TDNiCr) and Udimet 700 (U700) for the shells, are difficult to weld by conventional fusion welding processes.

General Electric has further developed a new joining process, activated diffusion brazing, which produces in ultra high strength gas turbine alloys, crack-free joints with strengths approaching base metal properties. This process combines the manufacturing ease of brazing with the high joint efficiencies of solid state diffusion bonding. The process involves joining nickel base superalloy components with a specially designed bonding alloy that completely melts at some elevated temperature below the incipient melting point of the alloy or alloys being joined. Subsequent to this, the joined component is given a diffusion heat treatment to effect homogenization of the bonding alloy and base metal. This is followed by an appropriate aging heat treatment. The process differs radically from solid state diffusion bonding in that only nominal pressures (0 - 15 psi) (0 - 103 k Pa) are required to produce a sound joint. The low pressure used in this process allows it to be used for joining relatively fragile parts of complex configurations without risking deformation during joining.

Although applicable to many superalloys, initial development of the activated diffusion bonding process was concentrated on producing high integrity joints in Rene' 80 as reported elsewhere (Reference 2). Extensive experience to date has shown this process to maintain the manufacturing ease of vacuum furnace brazing while developing high joint strengths in Rene' 80. Joint strengths several times those produced with conventional brazing alloys are achieved.

The process provides a major advantage in metal joining technology and is far superior to conventional welding, brazing, or solid state diffusion bonding of superalloys because of its ability to produce sound, strong, crack-free joints in complex configurations.

While terminology for this process has not been sanctioned by the American Welding Society Committee on Definitions and Symbols, it will be referred to as activated diffusion brazing throughout the remainder of this report.

Thus, the activated diffusion brazing process was selected to provide a high strength joint between the finned shells and airfoil strut. The joining process was to be applicable to complex turbine blades with twist, compound curvature, and variable chord widths.

The objective of this program was to develop reliable joining techniques for attaching airfoil shells with complex internal cooling passageways to high temperature resistant strut materials without damaging the internal cooling configuration or other parts of the blade.

The joining development work was concentrated on establishing the feasibility of reliably joining the finned shells to the struts. Tip cap attachment, trailing edge and shell to blade platform joining were conducted with minimal development effort.

The objectives of this program were accomplished in a three-task program:

Task I - Process Development - The activated diffusion brazing process procedure and brazing parameters for attaching TDNiCr and U700 finned shells to Rene' 80 struts were defined. Among the joining variables investigated were filler material compositions, filler material preplacement, joint clearances, effect of time, temperature, pressure, and post brazing heat treatment. The joining parameters were selected initially using metallographic examination for sound joints. Subsequently, RT and 1750°F (1228 K) joint efficiency of of overlap finned shear specimens were determined. Testing was conducted on both material combinations, with fins perpendicular and parallel to the tensile axis of the specimens.

In addition, butt joint tensile and stress rupture properties at 1750°F (1228 K) were determined for each material combination in the conventionally heat treated and exposed (1750°F (1228 K)/100 hr in air) conditions.

Task II - Property Evaluation - This task consisted of butt joint tensile (RT and 1750°F) (1228 K) and stress rupture (1600, 1750, and 1900°F) (1144, 1228, and 1311 K) testing of conventionally heat treated and cyclic exposed (1750°F (1228 K) 1200 hr in air/13 cycles) short transverse finned specimens which simulated the finned shell to strut joint.

Task III - Fabrication of Finned Shell Blades - Finned shell to strut blades of each material combination were fabricated in this task. The blades were completely finished with tip caps attached, trailing edge and shell base sealed, and film cooling holes in the shell. Several blades were destructively evaluated for joint quality. Six completed blades were delivered to NASA.

It was anticipated at the outset of this work that the joining technology developed would be directed toward the finned-shell to strut blade, but because of the materials involved, would be generally applicable to the whole field of fabricated complex turbine blades and vanes.

3.0 EXPERIMENTAL PROCEDURE AND RESULTS

The description of experimental procedure and results has been separated into four sections:

- Materials
- Task I - Property Evaluation
- Task II - Property Evaluation
- Task III - Fabrication of Finned Shell Blades

3.1 MATERIALS

The materials used in this work were procured and certified in accordance with General Electric materials specifications. In addition, 1750°F (1228 K) testing was conducted since it represented a typical metal temperature in a finned shell-strut blade design during engine operation. Table I gives the chemical composition of the materials used. These materials were:

- Finned Shells
- Cast Struts
- Brazing Filler Metal

3.1.1 Finned Shells

TDNiCr, 0.060 in. (1.5 mm) sheet was purchased from Fansteel. Tensile and stress rupture properties are given in Table II. Since TDNiCr properties are not affected by heat treatments below 2400°F (1589 K), no testing was conducted after exposure to the activated diffusion brazing heat treating cycle. The TDNiCr specification minimum values are given for comparison. The subject sheet met or exceeded all specifications requirements. This sheet was used throughout the program.

U700, 0.060 in. (1.5 mm) sheet was procured from Union Carbide. The sheet was not a production item, rather the product of an Air Force Program to establish a manufacturing process for improved high strength superalloy sheet (Reference 3). Tensile and stress rupture properties are given in Table III. Also included in Table III are the properties of U700 after being exposed to the activated diffusion brazing thermal cycle. Although the activated diffusion brazing thermal cycle altered U700 properties (decreased RT ductility, increased 1750°F (1228 K) strength), the resultant properties were adequate for the intended use - the finned shell to strut blade. This sheet was used throughout the program.

3.1.2 Cast Struts

Rene' 80, 1/8 x 1-1/2 x 3 in. (3.2 x 38 x 76 mm) plates were investment cast by the General Electric Development Foundry. These plates were only used for Task I work. Tensile and stress rupture properties are given in Table IV. The Rene' 80 met or exceeded standard Rene' 80 properties except 1800°F (1255 K) stress rupture strength. Since the specimen design selected for Task I (for which this material would be used) prevented Rene' 80 failure, this material was considered acceptable.

Rene' 80, 1-1/8 x 1-1/8 x 2 in. (28 x 28 x 51 mm) were investment cast by Misco Division of Howmet Corporation. These blocks were only used for Task II work. Since these specimens were used as mechanical extensions, only vendor certification of chemical composition was required.

Cast Rene' 80 first stage turbine blades for the General Electric CF6 engine were used throughout the Task III work.

3.1.3 Brazing Filler Metal

Only the chemical composition of the filler alloys was determined and is given in Table I for the activated diffusion brazing alloys, General Electric B-1 and General Electric B-28, hereafter referred to as B-1 and B-28, respectively. Coast Metal 50 was used in Task III for tip cap attachment, therefore its composition is also included. The compositions of each of these alloys was acceptable.

3.2 TASK I - PROCESS DEVELOPMENT

To aid in appreciating the various details explored under process development, the description of this work has been divided into several sections:

1. Fin machining
2. Joining criteria
3. Joining development for TDNiCr - Rene' 80
4. Shear properties of TDNiCr - Rene' 80 joints
5. Butt joint properties of TDNiCr - Rene' 80
6. Joining development for U700 - Rene' 80
7. Shear properties of U700 - Rene' 80 joints
8. Butt joint properties of U700 - Rene' 80 joints
9. Overall evaluation of results

3.2.1 Fin Machining

The airfoil shell fin geometry is shown in Figure 2. While alternate fin geometries were considered (wider fins and wider spacings), the geometry shown in Figure 2 was considered representative and was used exclusively in this program. Electo-discharge machining was chosen to produce the finned configuration. The fins were machined simultaneously on each specimen using 0.024 in. (0.61 mm) thick brass sheet electrodes separated by 0.016 in. (0.4 mm) insulation. The sheets were rigidly fixtured to prevent distortion during machining. Accurate control of machining parameters and insulating fluid flow in combination with the "ganged" electrodes produced precise uniform fin geometry.

Machining tolerances consistently achieved throughout this work on the critical fin dimensions were:

Fin width:	0.012 ± 0.002 in.	(0.30 ± 0.05 mm)
Fin spacing:	0.028 ± 0.002 in.	(0.71 ± 0.05 mm)
Fin depth:	0.025 ± 0.002 in.	(0.64 ± 0.05 mm)

Examples of the uniformity of fin configurations are shown throughout the report (note in particular Figures 3, 5, and 60). Because of the precise dimensional control required, the machining parameters were controlled to produce a minimum of surface disruption. The metallographic cross sections cited above are typical examples of the smooth machined surfaces produced between the fins.

3.2.2 Joining Criteria

As mentioned previously, joining development was to be minimal for tip cap attachment, trailing edge and shell to platform sealing. Conventional welding and brazing technology was to be used to produce these joints.

However, detailed criteria were specified for the finned shell to strut joints:

a. A minimum of 90 percent of the contracting area shall be welded. The length of the maximum acceptable non-welded defect shall not be greater than 0.05 in. (1.3 mm), and in each fin any two adjacent defects shall be separated by at least their total combined lengths. Defects separated by less than this distance and agglomerations of defects measuring less than 0.05 in. (1.3 mm) shall be considered single defects.

b. Air passages shall not be clogged or otherwise obstructed.

c. The deformation of fins during joining shall not reduce cross section of air passages by more than 15 percent. If, however, it can be shown that the process requires greater deformation, and that the air passage cross sectional areas can be reproduced within ± 5 percent area, the above requirements may be waived by the NASA Project Manager.

d. The joining process shall not lower the 1600°F (1144 K) tensile properties of the strut material below:

   - Tensile strength - 90,000 psi (620 MPa)
   - Yield strength (0.2 percent offset) - 70,000 psi (483 MPa)
   - Reduction in area - 15 percent

e. The minimum joint shear strength at 1750°F (1228 K) shall result in stresses of 8000 psi for the TDNiCr, and 50,000 (345 MPa) for U700 finned shells joined to Rene' 80.

In addition to these criteria, the efficiency of butt joints in each material combination shall be determined in tensile and stress rupture at 1750°F (1228 K). Tensile efficiency (at 1750°F) (1228 K) of butt joints after exposure for 100 hr at 1750°F (1228 K) in air shall be determined.

3.2.3 Joining Development for TDNiCr - Rene' 80

The basic joining parameters which were defined to produce sound, strong activated diffusion brazed joints in finned TDNiCr to Rene' 80 were:

a. compatible heat treatment
b. surface preparation
c. bonding alloy composition
d. bonding alloy preplacement technique
e. joint gap clearance
f. bonding pressure

The compatible heat treatment selected was simply the conventional Rene' 80 heat treatment since TDNiCr's inherent stability negates any property changes through heat treatment below 2400°F (1589K). All heat treatments and joining operations were conducted in vacuum (10^{-4} Torr) (1.3 cPa) unless otherwise noted.

The heat treatment, therefore, was:

• prebrazing heat treatment:	TDNiCr - none Rene' 80-2225°F (1491 K)/2 hr
• brazing temperature/time:	2230 ± 10°F (1499 ± 6 K)/25 min
• postbrazing heat treatment:	2000°F (1366 K)/4 hr 1925°F (1325 K)/4 hr 1550°F (1089 K)/16 hr

This heat treatment was used throughout the program for the TDNiCr - Rene' 80 material combination unless otherwise noted.

The surface preparation used on all joint faying surfaces was a conventional surface grind to approximately 16 RMS finish. Immediately prior to joining, the surfaces were degreased to provide a clean surface. Rene' 80 was given the standard homogenization heat treatment (2225°F (1491 K)/2 hr) prior to activated diffusion brazing. Elimination of this step invariably resulted in poor joint quality (large voids, or unwetted regions).

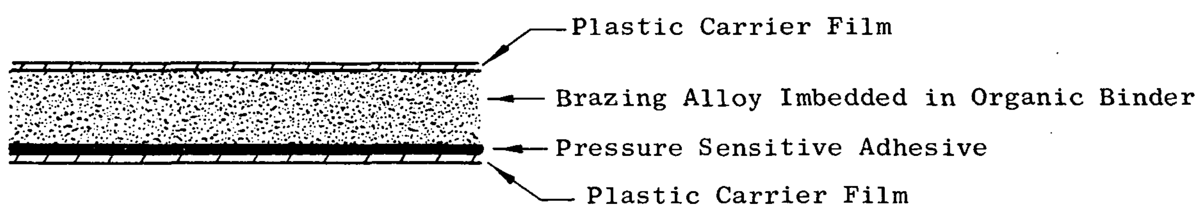
As will be discussed later, electroplated nickel on the TDNiCr surfaces was evaluated in an attempt to improve joint quality, but this procedure was not a surface preparation, per se.

Thus the combination of Rene' 80 prebrazing heat treatment, surface grinding, and degreasing was used throughout this program as the standard surface preparation.

Two brazing alloy compositions initially selected were; B-28 (Rene' 80 + 2 percent B) and B-1 (Rene' 80 + 5 percent Si). The chemical compositions of the alloys are listed in Table I. These alloys were developed for use with the activated diffusion brazing process and have demonstrated ability to produce high strength joints in Rene' 80 and other nickel base superalloys. Joints were made between finned shells of TDNiCr and Rene' 80 using each of the alloys. Typical photomicrographs of the resultant joints are shown in Figure 4. Sound joints were produced with both alloys. Generous, uniform fillets were formed at the juncture of the TDNiCr fins and Rene' 80. However, severe penetration of the boron into the TDNiCr fin occurred in joints made with B-28 (top of Figure 4). This deep diffusion of boron into the TDNiCr severely impaired the thoria dispersion and grain texture. The diffusion of silicon into TDNiCr (bottom of Figure 4) from the B-1 alloy was much less, so B-1 was preferred for joining TDNiCr to Rene' 80.

The brazing alloy preplacement technique was considered one of the most critical portions of this work. The high strength requirements necessitated sound joints, yet it was imperative that none of the cooling passages be blocked because of the resultant decrease in cooling air flow. Also the cooling passages were so small (0.025 x 0.028 in) (0.64 x 0.71 mm) that they acted as capillaries in the presence of molten brazing alloy. Precise metering of brazing alloy to provide both sound joints and prevent passage clogging was deemed necessary.

This was accomplished by imbedding the bonding alloy powder in selected organic binders, producible as sheet at specified thickness. This is commercially available processing from Vitta Corporation, Wilton, Connecticut. The brazing alloy power in the organic binder sheet is known as transfer tape and has a pressure-sensitive adhesive coating on one surface to facilitate placement on the metal surfaces to be joined. The sheet is protected on both sides by plastic carrier films (much like a Band-Aid) which are removed prior to use. The composite sheet is sketched in cross section below:



The transfer tape has the advantage of being flexible, can be readily cut to complex shapes, and can be produced to precise uniform thickness. Cast or brittle materials can be produced as powders and used in sheet form through this process.

In all cases, the sheet was preplaced on the Rene' 80 side of the joint. During brazing, as the alloy melted and flowed, generous fillets were formed at the juncture of the TDNiCr fins and Rene's 80 as shown in many photographs throughout the report (see Figures 4, 5, and 60).

A considerable number of 1 in. (25.4 mm) square flat finned shell specimens were joined to Rene' 80 using the B-1 brazing alloys in thickness of 0.003 in. (0.08 mm) and 0.006 in. (0.15 mm) to determine the proper transfer tape thickness. Specimens were brazed in the positions to be encountered during blade manufacturing, that is, with fins down and with fins up. A summary of the specimens joined is given in Table V. A typical joined specimen is shown in Figure 5A. Passage clogging was encountered randomly with the use of either 0.006 in. (0.15mm) B-1 or B-28 brazing alloys, indicating this alloy thickness to be too great. The use of 0.003 in. (0.08 mm) brazing alloy transfer tape consistently produced joined specimens without clogged passages. Conventional brazing alloy "stop-off" and fin position during joining had no effect on passage clogging.

One of the disadvantages of using the transfer tape was the inability of the vendor to supply consistent quality tape. The organic binders are selected to completely volatilize in vacuum at a temperature well below the brazing temperature. Usually volatilization is in the 500-1000^{o}F (533-811 K) temperature range. The initial lot of transfer tape used in this program left no residue as is evident in Figure 4. This method of preplacement was successfully used exclusively in Task I, as well as in selected specimens of Tasks II and III. Subsequent lots of transfer tape contained excessive non-volatile residue which made them unacceptable.

Investigation of plasma spraying as a brazing alloy preplacement technique provided an attractive backup method of applying the alloy. This method used no binder, but simply applied the required amount of alloy to the joint faying surfaces. Plasma spraying proved to be difficult, but an effective means for precisely metering the brazing alloy will be discussed under Task II.

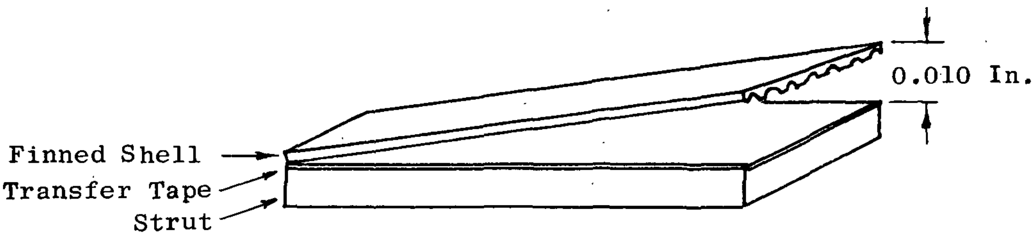
Our overall comparison of the two preplacement techniques, transfer tape or plasma spray is:

a. Transfer tape is an inexpensive, versatile means of precisely metering brazing alloy, but is sometimes of variable quality.

b. Plasma sprayed powders generally produce more sound joints (less voids), are of consistently high quality, but are more difficult to precisely meter. (This limitation may become more severe with more complex joint configurations). Of course, plasma spraying facilities are required.

It was beyond the scope of this program to further troubleshoot the transfer tape quality problems. It was concluded from this work that either plasma spray or transfer tape would adequately preplace the brazing alloy, provided good quality transfer tape could be produced.

The maximum joint gap clearance which could be bridged was evaluated because a severe limitation to producing the finned shell to strut would be the fit-up tolerance between fins and strut. Casting tolerance, sheet metal forming tolerance, sheet variations, etc., all add to potential joint gap. An attempt to identify the maximum gap which could be bridged utilized a finned shell joined to a Rene' 80 strut with gap varying from 0 to 0.010 in. (0.25 mm) as shown below.



When 0.006 in. (0.15 mm) transfer tape was used, a 0.006 in. (0.15 mm) gap could be consistently bridged; when 0.003 in. (0.008 mm) thick transfer tape was used, a 0.003 in. (0.08 mm) gap could be consistently bridged. This dictated the maximum mismatch which could be tolerated in a finned shell to strut assembly.

The effect of brazing pressure, over the range of 0-40 psi (0-276 kPa), on joint quality was examined metallographically as shown in Figure 6. Joints made at 0 psi contained large voids while very little difference was evident between joints made at 15 (103 kPa) and 40 psi (276 kPa). A nominal brazing pressure of 15 psi (103 kPa) was used for the remainder of this program unless otherwise stated.

3.2.4 Shear Properties of TDNiCr - Rene' 80 Joints

In addition to the joining parameters defined through metallographic examination of joint quality as described above, tensile and stress rupture testing was conducted on finned overlap shear specimens, to further define bonding parameters, and establish joint efficiencies.

The finned overlap shear test specimens are shown in Figure 7. The activated diffusion brazing parameters, as described above, were:

- prebrazing heat treatment: TDNiCr - None; Rene' 80 - 2225°F (1491 K)/2 hr
- surface preparation: ground and degreased (or the TDNiCr was nickel electroplated if so indicated in the Tables to follow)
- brazing alloy: 0.003 in. (0.08 mm) thick B-1 transfer tape preplaced on the Rene' 80 side of the joint
- brazing temperature/time: 2230 ± 10°F (1494 ± 6 K)/25 min
- brazing pressure: 15 psi (103 kPa)
- postbrazing heat treatment: 2000°F (1366 K)/4 hr; 1925°F (1325 K)/4 hr; 1550°F (1089 K)/16 hr

All specimens were examined for any evidence of passage clogging which was noted in the tables of data.

The following is a list of the work conducted to define shear joint efficiencies.

a. RT shear tensile with fins parallel to the load axis - Table VI, Figure 8.
b. RT Shear tensile with fins perpendicular to the load axis - Table VI, Figure 8.
c. 1750°F (1228 K) shear tensile with fins parallel to the load axis - Table VI, Figure 8.
d. 1750°F (1228 K) shear tensile with fins perpendicular to the load axis - Table VI, Figure 8.
e. Parent metal TDNiCr 1750°F (1228 K) short transverse shear tensile - Table VI, Figure 8.
f. 1750°F (1228 K) shear stress rupture with fins parallel to the load axis - Table VII, Figure 9.
g. 1750°F (1228 K) shear stress rupture with fins perpendicular to the load axis - Table VII, Figure 9.
h. Parent metal TDNiCr 1750°F (1228 K) short transverse shear rupture - Table VII, Figure 9.

Figures 8 and 9 show high joint efficiencies with failures occurring primarily in the fins far removed from the joint. Typical fracture appearances are shown in Figure 10. Although a weak zone is formed in the TDNiCr adjacent to the joint (as will be discussed in detail in the following section), the finned joint design and the inherent fillets formed around each fin, forced failure to occur outside the joint. This filleting is apparent in Figure 10. The short transverse shear tests on TDNiCr parent metal confirm the shear tensile strengths indicated by the activated diffusion brazed specimens. The shear stress rupture result on the parent metal specimen was superior to that determined by the joined specimens. Since failures occurred in the base metal, in both cases, this difference may have resulted from the different specimen design, thermal stress, or coefficient of thermal expansion.

3.2.5 Butt Joint Properties of TDNiCr - Rene' 80

To supplement the finned shear joint strength data (which closely simulated the stress state within a finned shell-strut blade), butt joint strength data were generated. The butt joint specimen is shown in Figure 11. The joining parameters were as described previously for finned joint specimens. Assembly of the butt joint specimens utilized a difference in material thickness along with a sacrificial nickel shim to allow generous billeting of the B-1 alloy during brazing. The shim prevented penetration of excess braze alloy into the sheet material, thus minimizing the braze alloy affected zone.

The following is a list of the work conducted to define the butt joint efficiencies.

a. 1750°F (1228 K) butt joint tensile in the conventionally heat treated condition - Table VIII, Figure 12.
b. 1750°F (1228 K) butt joint tensile after 1750°F (1228 K)/100 hr air exposure - Table VIII, Figure 12.
c. 1750°F (1228 K) butt joint stress rupture in the conventionally heat treated conditions - Table IX, Figure 13.
d. 1750°F (1228 K) butt joint stress rupture after 1750°F (1228 K)/100 hr air exposure - Table IX, Figure 13.
e. 1750°F (1228 K) butt joint stress rupture with no post brazing heat treatment - Table IX, Figure 13.

Although the butt joint tensile tests exhibited high joint efficiencies (see Figure 12), the stress rupture results detected a weak zone in the joint, heretofore undetected by shear tensile or stress rupture or butt joint tensile tests. The tensile and stress rupture failure locations were similar. The fracture appearances and metallographic examination of the typical failure locations are shown in Figures 14 through 18. This series of pictures shows the failures occurring in the TDNiCr immediately adjacent to the fusion line, at considerably lower strength than standard TDNiCr (as shown in Figure 13). The reason for the strength loss is evident in Figures 16 and 17. Both agglomeration and depletion of the ThO_2 has occurred because of the diffusion of silicon from the B-1 brazing alloy into the TDNiCr. Electron microprobe traces were made which confirmed the presence of silicon in the TDNiCr. This diffusion of solicon into TDNiCr was sufficient to disturb the THO_2 dispersion and reduce the strength in a narrow band adjacent to the molten zone. Attempts to reduce or eliminate this narrow, weak zone in the TDNiCr by nickel electroplating the TDNiCr (to prevent diffusion) or by elimination of the post brazing heat treatment were unsuccessful as shown in Figure 13. This weak region can be very narrow but the butt joint stress rupture test was sufficiently sensitive to detect it. The reduction in tensile strength after 1750°F (1228 K)/100 hr exposure (see Figure 12) was probably caused by further silicon diffusion into the TDNiCr, thus widening the weakened zone sufficiently that even the tensile test detected the weakness.

3.2.6 Joining Development for U700 - Rene' 80

The basic joining parameters which were defined to produce sound, strong, activated diffusion brazed joints in finned U700 to Rene' 80 were:

a. compatible heat treatment
b. surface preparation
c. brazing alloy composition
d. brazing alloy preplacement techniques
e. joint gap clearance
f. brazing pressure

With the exception of a, c, and d above, the joining development from the TDNiCr - Rene' 80 material combination was directly applicable to the U700 - Rene' 80 material combination, so items b, e, and f will not be discussed in this section.

The compatible heat treatment selected for the U700 - Rene' 80 material combination consisted of the activated diffusion brazing joining cycle (2200°F + 15°F at 0°F) (1478 K + 9 K, -0 K)/25 min plus the standard aging cycles for U700. As seen below, the aging cycles for U700 and Rene' 80 nearly coincide except for the 1400°F (1033 K) age which Rene' 80 does not normally receive. This aging in no way was detrimental to Rene' 80.

	Standard Rene' 80 Heat Treatment	Standard U700 Heat Treatment
Solution	2225°F (1491 K)/2 hr	2125°F (1436 K)/1/2 hr
Overage	2000°F (1366 K)/4 hr	1950°F (1339 K)/4 hr
Coating Cycle	1925°F (1325 K)/4 hr	--
Age	1550°F (1089 K)/16 hr	1550°F (1089 K)/24 hr
Age	--	1400°F (1033 K)/16 hr

Therefore, the heat treatment used throughout the program for the U700 - Rene' 80 material combination unless otherwise noted was:

- prebrazing heat treatment: U700 - None
Rene' 80 - 2225°F/2 hr (1491 K)
- brazing temperature/time: $2200 \begin{smallmatrix}+15\\-0\end{smallmatrix}$ °F $(1478 \begin{smallmatrix}+9\\-0\end{smallmatrix}$ K)/25 min.
- post brazing heat temperature: 1950°F (1339 K)/4 hr
1550°F (1089 K)/24 hr
1400°F (1033 K)/16 hr

The same two brazing alloy compositions which were evaluated for use with TDNiCr - Rene' 80 were evaluated for activated diffusion brazing U700 to Rene' 80. Both alloy compositions, B-28 (Rene' 80 + 2%B) and B-1 (Rene' 80 + 5%Si), are listed in Table I. Joints were made between finned shells of U700 and Rene' 80 using each of the alloys. Since the incipient melting temperature of U700 is approximately 2225°F (1491 K), the brazing temperature was limited to a maximum of 2215°F (1486 K). This proved to be a severe limitation on the use of B-28 and eventually led to elimination of its use. Sound joints could not consistently be made with B-28, because the brazing temperature was close to the B-28 liquidus. The B-1 liquidus was approximately 25°F (14 K) lower than that of B-28, and sound joints could consistently be made with B-1. Typical examples are shown throughout the remainder of the report (see Figures 19, 37, 57, 60 and 65). Thus, for different reasons, B-1 was chosen as the brazing alloy for joining U700 to Rene' 80 as well as TDNiCr to Rene' 80.

The brazing alloy preplacement technique selected, as discussed previously, was an adhesive-backed transfer tape. As was the case with the TDNiCr - Rene' 80 joints, a considerable number of U700 finned specimens were joined to Rene' 80 using both B-1 and B-28 alloys in the thicknesses of 0.003 in. (0.08 mm) and 0.006 in. (0.15 mm) to determine the proper transfer tape thickness. Specimens were joined in the positions to be encountered during blade manufacture, that is, with fins down and with fins up. A summary of the specimens joined is given in Table X. Passage clogging was randomly encountered when using the 0.006 in. (0.15 mm) thick transfer tape. The use of 0.003 in. (0.08 mm) thick transfer tape consistently produced sound joints with no passage clogging. Conventional brazing alloy "stop-off" and fin position during joining had no effect on passage clogging. Use of the 0.003 in. (0.08 mm) thick transfer tape, and as discussed previously, plasma spraying were both used throughout the remainder of the program as the brazing alloy preplacement techniques.

3.2.7 Shear Properties of U700 - Rene' 80 Joints

As previously described for TDNiCr - Rene' 80 joints, identical tensile and stress rupture testing was conducted on U700 to Rene' 80 finned overlap shear specimens to establish joint efficiencies. The finned overlap shear specimens are shown in Figure 7. The activated diffusion brazing parameters were:

• prebrazing heat treatment:	U700 - None Rene' 80 - 2225°F/2 hr (1491 K)
surface preparation:	ground and degreased
brazing alloy:	0.003 in. (0.08 mm) thick B-1 transfer tape preplaced on the Rene' 80 side of the joint
• brazing temperature/time:	$2220 {}^{+15}_{-0}$ °F ($1478 {}^{+9}_{-0}$ K)/25 min.
brazing pressure:	15 psi (103 kPa)
• post brazing heat temperature:	1950°F (1339 K)/4 hr 1550°F (1089 K)/24 hr 1400°F (1033 K)/16 hr

All specimens were examined for any evidence of passage clogging which was noted in the tables of data.

The following is a list of the work conducted to define finned shear joint efficiencies.

a. RT shear tensile with fins parallel to the load axis - Table XI, Figure 20.
b. RT shear tensile with fins perpendicular to the load axis - Table XI, Figure 20.
c. 1750°F (1228 K) shear tensile with fins parallel to the load axis - Table XI, Figure 20.
d. 1750°F (1228 K) shear tensile with fins perpendicular to the load axis - Table XI, Figure 20.
e. 1750°F (1228 K) stress rupture with fins parallel to the load axis - Table XII, Figure 21.
f. 1750°F (1228 K) stress rupture with fins perpendicular to the load axis - Table XII, Figure 21.

The finned shear strengths of the U700 - Rene' 80 joints were consistently high, and as shown in Figure 21, the stress rupture strength approached predicted base metal strength. Failures, however, invariably occurred through the joint, and fracture appearance at all test temperatures appeared similar to the specimen shown on the top of Figure 10. A graphic comparison illustrating the superior shear strengths produced in the U700 - Rene' 80 versus those produced in TDNiCr-Rene' 80 can be seen by comparing Figures 8 and 9 with Figures 20 and 21 respectively.

3.2.8 Butt Joint Properties of U700 - Rene' 80 Joints

To supplement the finned shear joint strength data (which closely simulated the stress state within a finned shell-strut blade), butt joint strength data were generated. The butt joint specimen is shown in Figure 11. The joining parameters were as described previously for finned joint specimens.

The following is a list of the work conducted to define the butt joint efficiencies.

a. 1750°F (1228 K) butt joint tensile in the conventionally heat treated condition - Table XIII, Figure 22.
b. 1750°F (1228 K) butt joint tensile after 1750°F (1228 K)/100 hr air exposure - Table XIII, Figure 22.
c. 1750°F (1228 K) butt joint stress rupture in the conventially heat treated condition - Table XIV, Figure 23.
d. 1750°F (1228 K) butt joint stress rupture after 1750°F (1228 K)/ 100 hr air exposure - Table XIV, Figure 23.

As shown in Figure 22, the tensile efficiency of the joints based on Rene' 80 was approximately 80%, while the stress rupture efficiency based on U700 was approximately 60%, as shown in Figure 23. The 1750°F (1228 K)/100 hr air exposure had no effect on tensile properties but actually improved the stress rupture properties (see Figure 23). The improvement apparently resulted from diffusion occurring at the joint. The failures in each of the specimens occurred through the center of the joint.

Since no degradation occurred in the U700, the butt joint tensile and stress rupture strengths were significantly higher than those achieved in the TDNiCr - Rene' 80 joints. This can be seen by comparing Figures 12 and 13 with Figures 22 and 23, respectively.

3.2.9 Overall Evaluation of Results

The Task I work demonstrated the ability of the activated diffusion brazing process to produce sound, strong joints in the finned TDNiCr and U700 shell to Rene' 80 strut material combinations. In addition to the sound joints produced, each fin was contoured with a generous fillet at its juncture with the strut, thereby reducing any stress concentration. Freedom from any passage clogging further demonstrated the utility of the activated diffusion brazing process for joining finned shells to struts.

Joint strengths, both shear and butt, in the U700 - Rene' 80 were consistently high. In contrast, a weak zone was formed in the TDNiCr - Rene' 80 joints, but the finned joint design negated this shortcoming. In fact, shear tests resulted in several parent metal failures indicating very high joint efficiencies.

These encouraging joint strengths coupled with joint soundness and freedom from fin passage clogging provided a sound basis for continuing into Task II where a more rigorous evaluation of properties was made.

3.3 TASK II - PROPERTY EVALUATION

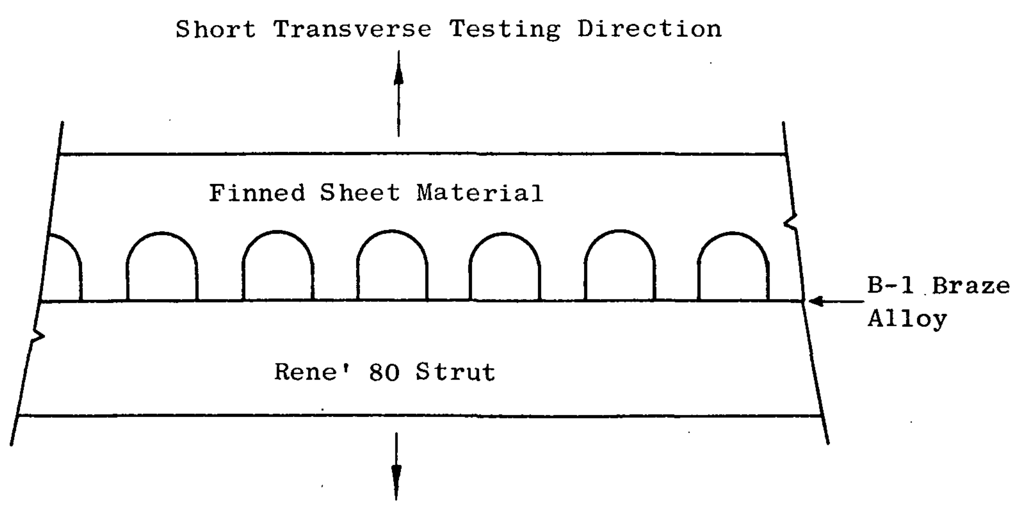
The tensile (RT and 1750°F (1228 K)) and stress-rupture properties of conventionally heat treated and cyclic exposed finned shell-strut activated diffusion brazed butt joint specimens were determined. This testing established the joint strength normal to the blade surface. The activated diffusion brazing parameters and techniques established in Task I for the two material combinations (TDNiCr - Rene' 80 and U700 - Rene' 80) were used throughout Task II.

The description of the work done under Property Evaluation has been divided into several sections:

1. Specimen design
2. Specimen manufacture
3. Mechanical testing
4. Evaluation of mechanical testing results
5. Overall evaluation of results

3.3.1 Specimen Design

To evaluate the properties of finned sheet material activated diffusion brazed to Rene' 80, in the short transverse direction, the Task II short transverse finned butt joint specimen was designed (see Figures 24 and 25). Henceforth, the specimen will be called a short transverse finned specimen. The properties determined in this section would simulate those required to separate the sheet material finned shell from the Rene' 80 strut as shown in the sketch below:



Initially an attempt was made to join a 0.060 in. (1.52 mm) TDNiCr 1 x 1 in. (25 x 25 mm) wafer with fins on one side to a Rene' 80 clevis block (see Figure 24) and the other flat side with no fins to another Rene' 80 clevis block. The effective cross-sectional area of the finned joint was about 0.3 sq. in. (194 sq mm) as compared to 1.0 sq. in. (645 sq mm) for the joint between the flat surfaces. It was anticipated that such a difference in areas would cause the specimen to fail at the finned joint or in the fins themselves when tested. However, after tensile testing some specimens at 1750°F (1228 K) it was found that the joint between the flat surfaces was of very poor quality. Therefore, several different techniques were tried to determine the reason(s) for the poor joints and subsequently to determine the best method to join the back side of the finned wafer to a Rene' 80 clevis block. Tensile testing at 1750°F (1228 K) was used as a basis for determining the success of each type of joint tried. A summary of these results is presented in Table XV.

The results of the initial testing indicated that the use of transfer tape between two relatively large flat surfaces produced a poor joint. It was concluded that the binder was unable to volatilize and escape completely from the center of such a large area.

To allow the binder to escape during heatup, fins were put on the back side of the sheet metal wafers. These fins were wider and shorter to force failure in the standard fins. Since the fins were wider, the cross-sectional area of the back side joint would still be greater, forcing failure to occur at the standard joint or in the standard fins.

The shorter fins prevented excessive material from being removed from the sheet metal wafers. They also would make hole plugging easier which again would increase the cross-sectional area.

Preplacing the alloy by plasma spraying eliminated the problem of volatilizing the binder from the braze alloy since none was used. Plasma spraying several different thicknesses of braze alloy to produce maximum fillet size without hole plugging for the standard fins was evaluated. Approximately 0.004 in. (0.10 mm) was found to be the ideal amount for the standard fins and approximately 0.007 in. (0.18 mm) was found to cause the desired plugging of the back side fins.

Finally, it was determined that the final specimen should be assembled as shown in Figure 24. The actual technique used to assemble the specimen is presented later in the report.

3.3.2 Specimen Manufacture

Making the short transverse finned specimens involved the following processing techniques:

- Preparation of component parts
- Assembly
- Activated diffusion brazing
- Coating (If used)
- Heat Treatment
- Cyclic exposure (If used)

The preparation of component parts was essentially the same as that used in Task I work. Preparation of the sheet material, the Rene' 80 and the brazing alloy, are discussed separately below.

Before Electro-Discharge machining the fins into the 0.060 in. (1.52 mm) sheet material (TDNiCr or U700), it was ground flat and parallel on both sides. The sheet was sheared to the approximate wafer size and then the sides were precision ground to the final dimensions; 1 x 1 in. (25 x 25 mm) for TDNiCr and 0.8 x 0.8 (20 x 20 mm) for the U700 (see Figure 25). The only other preparation preceding assembly was to soak the finished wafers in acetone.

The Rene' 80 blocks were received in the as-cast condition. They were machined to their final Rene' 80 clevis block configuration as shown in Figures 24 and 25. The Rene' 80 clevis blocks were degreased with acetone and given a solution heat treatment (2225°F (1491 K)/2 hr) to promote sound joints. Just prior to assembly the Rene' 80 was again cleaned with acetone.

The B-1 brazing alloy in the form of 0.003 in. (0.08 mm) thick transfer tape was applied immediately preceding assembly. This was done to prevent the adhesive surface of the transfer tape from picking up contaminants such as dust particles. 0.007 in. (0.18 mm) of braze alloy was plasma sprayed on the back side joint.

When the alloy was preplaced by plasma spraying, the surface to be sprayed was lightly grit blasted to insure a better mechanical bond between the B-1 powder and the surface. Again the surfaces were assembled immediately to avoid the pickup of contaminants. Approximately 0.004 in. (0.10 mm) of braze alloy was plasma sprayed for the standard joint, and 0.007 in. (0.18 mm) of brazed alloy was used on the back side joint.

The assembly of the standard specimen was as follows (see Figure 26):

1. A Rene' 80 clevis block was plasma sprayed with 0.007 in. (0.18 mm) thick B-1 brazing alloy.
2. A U700 or TDNiCr wafer was then tack welded precisely in place with the shallow fins in contact with the plasma sprayed surface.
3. a) A 0.003 in. (0.08 mm) thick piece of transfer tape cut to the U700 or TDNiCr wafer side was applied to a second Rene' 80 block.

   -or-

3. b) A 0.004 in. (0.10 mm) thick layer of brazing alloy was plasma sprayed to the Rene' 80 block.

4. The assembly was then placed under a 300 lb (1335 N) load being careful to hold alignment and to prevent relative slippage of the component part.
5. Finally the assembly was held in place by spot tacking an 80%Ni-20%Cr strip on each side of the specimen.

The activated diffusion brazing was conducted in the same manner as in Task I. The assembled specimen was loaded into a vacuum furnace, and a weight was placed on top of the specimen to produce a pressure of approximately 15 psi (103 KPa) at the joint. The furnace was then evacuated to less than 1 x 10^{-4} Torr (1.3 cPa).

The brazing cycle began with a slow programmed heat-up rate of about 20°F (11 K)/minute to the respective brazing temperature. The brazing cycles were:

TDNiCr - Rene' 80 — 2230 ± 10°F (1494 ± 6 K)/25 min

U700 - Rene' 80 — $2200 \begin{smallmatrix}+15°F \\ -0°F\end{smallmatrix}$ $(1478 \begin{smallmatrix}\pm 9 \\ -0\end{smallmatrix}$ K)/25 min

Several U700 - Rene' 80 short transverse finned specimens were given a coating cycle after brazing, with the intent of improving the stress rupture life by reducing the amount of oxidation during subsequent cyclic exposure. The coating that was used was General Electric's Codep B, an aluminide coating.

The heat treatment of the activated diffusion brazed specimens was the same as discussed in Task I. After brazing, the TCNiCr - Rene' 80 short transverse finned specimens were given the standard Rene' 80 heat treatment, and the U700 - Rene' 80 specimens were given the standard U700 heat treatment. For convenience, a summary of all the heat treatments before, during, and after brazing is listed in Table XVI.

A cyclic exposure was given to some of the conventionally heat treated short transverse finned specimens to evaluate the effects of oxidation and thermal cycling on the mechanical properties of the specimen. These specimens were placed upright in an air furnace at 1750°F (1228 K) for a total of 200 hours. The specimens were removed from the furnace thirteen different times and permitted to cool to room temperature in air. The actual cyclic exposure was as follows:

1750°F (1228 K) for thirteen cycles; six 8-hr cycles, six 16-hr cycles, and one 64-hr cycle totaling 200 hr.

Periodic inspection at 60X was conducted to determine specimen deterioration, if any.

3.3.3 Mechanical Testing

The activated diffusion brazed short transverse finned specimens were tested by two independent sources; General Electric's M&PTL Materials Testing

Unit and Metcut Research. M&PTL Materials Testing Unit performed all of the tensile testing of both the U700 and the TDNiCr specimens, all of the coated U700 specimens and most of the stress rupture testing of the TDNiCr specimens. Metcut Research performed most of the stress rupture testing of the U700 specimens.

The mechanical properties of the Task II short transverse finned specimens were determined and the results are presented in both tabular and graphical forms.

3.3.3.1 TDNiCr - Rene' 80 Joints

1. Tensile properties (Table XVII, Figure 27)
2. Stress rupture properties (Table XVIII, Figures 28 and 29)

3.3.3.2 U700 - Rene'80 Joints

1. Tensile properties (Table XIX, Figure 30)
2. Stress rupture properties (Table XX, Figures 30, 31, and 32).

3.3.4 Evaluation of Mechanical Testing Results

3.3.4.1 TDNiCr - Rene' 80 Joints

The TDNiCr - Rene' 80 finned joints were consistently sound, with generous fillets at the fin to strut juncture. Figure 33 shows such a typical joint after brazing.

Both tensile and stress rupture testing of the short transverse finned specimens produced primarily fin failures, in many cases far removed from the joint region. Typical fracture appearances are shown in Figures 34 and 35. Thus, high joint efficiencies were consistently achieved with the short transverse finned specimens. However, this testing revealed that the short transverse tensile and stress rupture strengths of TDNiCr were significantly lower than those of the conventional longitudinal and transverse sheet directions.

In contrast to the butt joint specimens tested in Task I, which invariably failed in the weak region of the TDNiCr immediately adjacent to the molten zone, the specimens in Task II failed in the base metal. Although the weak region was still present, the fillets formed along the fins (see Figure 35) provided mechanical interlocking and increased shear area through the weak region of the joint. These conditions, in combination with the relatively weak short transverse shear strength of TDNiCr, resulted in the base metal fin failures - indicating high joint efficiency.

The cyclic exposed TDNiCr - Rene' 80 short transverse finned specimens were approximately 15 percent of the room temperature tensile strength of the unexposed specimens. The reason for this was attributed to the severe cracking which occurred in the fins' short transverse direction during iring cyclic oxidation. This cracking was labeled as stress accelerated oxidation cracking, a typical example of which is shown in Figure 36.

It was concluded that the double clevis block design (see Figure 24) was sufficiently rigid to induce thermal stresses in the sheet material when the specimen was heated and/or cooled. In order to determine the severity of the stresses, four specimens were manufactured using less restrained specimen designs.

Two of the specimens consisted of a single Rene' 80 clevis block and a finned TDNiCr wafer and the other two were made using 0.100 in. (2.5 mm) flat Rene' 80 wafer and a finned TDNiCr wafer. After activated diffusion brazing and fully heat treating, the four specimens were cyclic exposed exactly as the double clevis block specimens described before.

After exposure, Rene' 80 clevis blocks to facilitate testing were attached with an additional brazing step followed by standard aging heat treatments.

The results of room temperature tensile testing of these specimens are presented in Table XVII. As anticipated, the single Rene' 80 clevis block specimens had less cracking than the double Rene' 80 clevis block specimens; and the Rene' 80 wafer had less cracking than both of the other two designs. This resulted in corresponding increases in strength, but the cycles exposed TDNiCr - Rene' 80 specimens at best only reached 2/3 of unexposed strengths. Evidence of cracking was encountered in all of the cyclic exposed finned TDNiCr - Rene' 80 specimens - even those of the lowest restraint. Therefore, no further work was conducted on cyclic exposed TDNiCr - Rene' 80 short transverse finned specimens.

3.3.4.2 U700 - Rene' 80 Joints

The U700 - Rene' 80 joints were consistently sound, with generous fillets at the fin to strut juncture. Figure 37a shows such a typical joint after brazing. Figure 37b shows the same type of joint except fins were coated.

In general, the U700 - Rene' 80 short transverse finned specimens failed in the joint during testing (see Figures 38 and 39). However, during stress rupture testing, as the strength of the joint approached parent metal strength, failures began to propagate up into the fins (see Figures 40, 41 and 42). This "combination" failure was particularly true at higher temperatures.

The 1750°F (1228 K) tensile strength of the U700 - Rene' 80 short transverse finned specimens was approximately 40 ksi (276 MPa), which was about 67 percent of the Rene' 80 parent metal strength, and about 80 percent of the Task I butt joint strength. This comparison is clearly shown in Figure 30. For the cyclic exposed specimens the RT and 1750°F (1228 K) tensile strengths were about the same as unexposed specimens. This supported the results obtained in the Task I work on uncycled, exposed butt joint specimens.

The 1750° stress rupture strength of the U700 - Rene' 80 finned joint was 100 percent of the U700 base metal strength. The strength of the cyclic exposed specimens was approximately 65 percent of the U700 base metal.

The strength of the coated and cyclic exposed specimen was about 60% of the U700 base metal. (See Figures 31 and 32).

As mentioned above, the cyclic exposure of the U700 - Rene' 80 combination caused a significant loss in stress rupture life. In the case of uncoated specimens, this was attributed to the oxidation of the brazed joint (see Figures 43 and 44).

The stress rupture testing of the cyclic exposed specimens in the high stress-low temperature range revealed a very wide scattering of data. In fact, three of the specimens tested at 1600°F (1144 K) (20, 25 and 30 ksi) (138, 172 and 207 MPa) failed on loading. Close examination of testing procedure revealed that the loading time was the same for all the specimens which meant that the higher stressed specimens (which required loads close to 6000 lb (26.7 KPa)) were loaded at the highest rate (approximately 20,000 lb/min) (89 KPa/min). This had little effect on the unexposed specimens or the low stressed specimens, but where oxidation occurred in the cyclic exposed specimens, as shown in Figure 44 the joint appeared to be sensitive to strain rate.

To substantiate this, two stress rupture tests were run at 1600°F (1144 K) and 30 ksi (207 MPa) using a low loading rate (2,000 lb/min) (89 KPa/min) similar to that used on a tensile test. The specimens, as predicted, lasted significantly longer than those rapidly loaded. The results are summarized in Table XX and Figures 31 and 32.

As evidenced by the uniformity of the remainder of the stress rupture results, this strain rate sensitivity appeared to be confined to the high data points (above 20 Ksi) (above 138 MPa).

To eliminate the effects of oxidation during cyclic exposure, several specimens were coated with Codep B coating which is known to prevent oxidation of high temperature alloys in the range used for the testing. The coating did prevent oxidation during cyclic exposure. (See Figure 43b). Stress rupture testing of these coated specimens, however showed an actual reduction of life when compared to the uncoated and exposed specimens. The reason for this was attributed to the diffusion zone created by the coating which was known to be weak. This in effect reduced the cross-sectional area of the test joint.

However, the loss of area was not enough to explain the total drop from the strength determined by the uncycled specimens. Two additional tests were conducted in an effort to discover the cause of strength loss which occurred during cyclic exposure. First, a coated and cyclic exposed specimen was resolution heat treated at 2100^{o}F-1 Hr in vacuum in an attempt to restore metallurgical damage which may have taken place during cyclic exposure. Testing of this specimen (C-6) showed no increase in stress rupture life (see Table XX). A second specimen (C-7) was stress rupture tested but not to failure so that possible cracking might be detected prior to failure indicating the cause of strength loss. Metallographic inspection however did not show any such cracking.

3.3.5 Overall Evaluation of Results

The short transverse finned specimen was designed to evaluate the finned shell-strut joint strength normal to the blade surface and adequately predicted these strengths.

Although a weak zone was detected in Task I butt joint specimens, the natural fillets formed along the fins in the actual finned shell to strut design forced failure to occur in the base metal far removed from the joint. The limiting strength in this design was the short transverse strength of TDNiCr, since failures did not occur at the joint.

The finned joints revealed inadequate strength in the TDNiCr to withstand the thermal cycling under the inherent restraint of the test specimens.

The U700 finned shell activated diffusion brazed to the Rene' 80 strut, on the other hand, was strong enough to yield about 67 percent of Rene' 80 parent metal tensile strength (see Figure 30) and 100 percent of U700 parent metal stress rupture strength (see Figure 32). The occasional fin failures encountered again showed that the joint design aided joint efficiency and occasionally caused parent metal failures.

The cyclic exposure of U700 - Rene' 80 short transverse finned specimens somewhat reduced the joint strength; oxidation which occurred during the 200 hr exposure at 1750^{o}F (1228 K) was believed to be the prime cause. However, lives of coated specimens where oxidation did not occur were also low. It's possible that rupture life was reduced by a combination of metallurgical damage during cycling and cross sectional area loss from the diffusion zone of the coating. However, the exact cause of reduced stress rupture properties after cyclic exposure was not determined.

3.4 TASK III - FABRICATION OF FINNED SHELL BLADES

The description of the work done under Task III has been divided into several sections:

1. Requirements
2. Formation of Finned Shells
3. Machining Blade Bleed Holes and Finned Shell Plenum Chambers
4. Activated Diffusion Brazing Trials
5. Processing of Remaining Components
6. Fabrication of Blades for NASA
7. Overall Evaluation of Results

3.4.1 Requirements

The objective of Task III was to activated diffusion braze six TDNiCr and six U700 finned shells to twelve Rene' 80 hollow cast airfoil struts for delivery to NASA. The first stage turbine blade for the General Electric CF6 engine was selected as the Rene' 80 component because it met the configuration requirements of possessing a variable airfoil, a twist, and a compound curvature. A drawing of the basic finned shell blade is shown in Figure 45. As shown in the drawing, the fins were in a chordwise or axial direction and extended over two-thirds of the pressure and suction faces of the turbine blade.

The fin geometry was the same as that used for the flat test panels for Tasks I and II. Plenum chambers were located at the leading and trailing edges of the turbine blade and in both finned shells near the No. 4 radial hole. Five equally spaced holes were electro-discharge machined in the blade on both sides of the blade's No. 4 radial hole and on both sides of shells at the leading and trailing edge plenum chambers. The major effort of Task III was to be expended toward developing procedures to produce sound joints between the fins and the outer surfaces of the blade. A number of other areas, such as the tip cap to the blade and shells to the platform were also to be joined; however, a minimum of development effort, employing best judgment techniques, was to be used for joining them. Four trial blade assemblies of each type material combination were fabricated using essentially the same activated diffusion brazing techniques established during Tasks I and II. Destructive techniques were employed to verify the quality of the joints. The quality requirements were that a minimum of 90 percent of the contacting area was to be diffusion brazed. The maximum length of any diffusion brazed defect was not to exceed 0.05 in. (1.3 mm) and any two adjacent defects were to be separated by at least their combined total lengths. Passageway clogging was to be avoided and the cross-sectional areas of the air passages were not to be reduced by more than 15 percent, due to fin deformation, during the joining process.

After the activated diffusion brazing trials were completed, the six TDNiCr and six U700 finned shelled blades were completed using the fabricating procedures developed on the trial blades for each material combination. However, no non-destructive tests were conducted on any of them. These procedures included the complete heat treatment of the blades enabling them to be considered hardware capable of being tested under environmental conditions similar to those encountered in a jet engine.

3.4.2 Formation of the Finned Shells

A specification was written for the forming of the finned shells and the fabrication of a pair of activated diffusion brazing dies. One or two possible techniques of manufacture of the shells were considered. The first was to be a completely formed shell from one piece of material. The second was to have the shell made in three or four sections that would later be joined by conventional welding or brazing. The second alternative was an expediency, in case some developmental effort was necessary to form the shell from one piece. The four sections were to be composed of an (a) pressure face shell, (b) suction face shell, (c) leading edge channel, and (d) trailing edge flat. The joint location for the leading edge was at the junction of the fin area and the leading edge plenum chamber. The finished shells' interior surfaces were to fall within a 0.002 in. (0.051 mm) contour band circumscribed around the contour sections on the pressure and section faces of a supplied blade with a finished airfoil on it. It was felt that working with a finished blade would produce components closer to the required tolerances than those made from glass masters.

Quotes were received from the outside vendors, and the Danville Metals Stamping Co., Inc., was selected to fabricate the shells and activated diffusion brazing dies. The second method of manufacture (to make the shells out of four sections) was selected. The shell material was supplied to the vendor and both the TDNiCr and U700 sheet were from the same heats of material used in Tasks I and II. The Rene' 80 first stage turbine blades were from production heats of material and the blocks for the activated diffusion brazing dies were the same heats of material as the clevis blocks used in the Task II work.

It was decided to form the pressure and suction face shells from flat material that contained the fin contour rather than form the shells and then machine the fin contour into them. As was the case in Tasks I and II, the electro-discharge machining process was selected to generate the fin contour into the flat sheets. Figure 46 shows the components after they were machined. No particular problems were encountered in machining the larger cross-sectional areas of the shells; however, the original thickness of the U700 was 0.060 in. (1.52 mm), and some difficulties, due to warpage in the sheet, were encountered in grinding it to the required 0.050 in. (1.27 mm). The leading edge and trailing edge thicknesses were 0.025 in. (0.64 mm) and there was sufficient TDNiCr available in this thickness to make the parts. This was not the case for the U700 and the 0.060 in. (1.52 mm) material had to be cold rolled down to 0.025 in. (0.64 mm). Grinding was not considered because of the high percentage of material that had to be ground off and the previous difficulties of holding the slightly warped sheet metal panels made it probable that grinding would not be successful. The rolling procedure was accomplished without any intermediate anneals, however the finished 0.025 in. (0.64 mm) sheet was solution annealed and flattened in vacuum at 2100°F (1473 K)/1/2 hr, inert gas cooled to stress relieve it, and put it in a soft condition for forming.

Figures 47 and 48 illustrate the shells after they were formed and had a 0.060 in. (1.52 mm) holding envelope around their outer periphery machined off. The TDNiCr shells were formed cold in one operation. Forming trials were made on the U700 shells with the same dies and it was found that the U700 was somewhat stiffer than the TDNiCr. Consequently, the forming dies had to be altered. The finned 0.050 in. (1.27 mm) U700 pressure and suction face sheets were also solution annealed in argon prior to forming at 2100°F (1473 K)/1/2 hr and water quenched. The shells were then formed cold in one operation without any difficulties. After all the components were formed, individual pieces of each configuration were selected, matched, and fit to the "base dimension" blade that was furnished for dimensional determinations and inspection.

The activated diffusion brazing dies were machined from blocks of Rene' 80. The Rene' 80 was selected as the die material to maintain compatibility between the coefficients of expansion and the dies and the components, and it was felt that it would have sufficient strength at the activated diffusion brazing temperature. It was also felt that this approach would present fewer problems than would be encountered using dies made of molybdenum or another material. The contact surfaces were to form a 0.002 in. (0.051 mm) contour band over the outer surfaces of the pressure face shell and suction face shell at the fin area in contact with the blade. The mean chord line at the center of the blade was to be on the split line between the two dies. Figure 49 shows the first pair of activated diffusion brazing dies. They were somewhat deficient in that they did not fully cover the finned area at the leading edge. Consequently, a second pair of closed dies was designed and ordered. However, the first pair was considered to be adequate for a portion of the four trial activated diffusion brazes that were contemplated and used for the TDNiCr shells.

3.4.3 Machining Blade Bleed Holes and Finned Shell Plenum Chambers

As noted in Figure 45, five equally spaced 0.030 in. (0.76 mm) diameter air passage "bleed" holes were required in No. 4 radial hole of the Rene' 80 blade. These were easily drilled by clamping the dovetail of the blade in a multiaxis vise to position the centerline of the radial hole in a horizontal plane. The bleed holes were then electro-discharge machined in the proper location using a 0.030 in. (0.76 mm) diameter brass tube. The blade bleed holes in the blade direct the cooling air into plenum chambers in the finned area of both the pressure and suction face shells. The centerlines for these center plenum chambers were located by positioning a matched pair of shells on the blade with masking tape on the finned surfaces, and transcribing the centerlines to the masking tape. The center plenum chambers were then milled on the centerline with a 0.250 in. (6.35 mm) diameter round end mill.

The trailing edge plenum chambers were milled to 0.300 in. (7.62 mm) from the end of each shell using a flat end mill. The contours of the shells in this area were essentially flat so no contour milling was required. Five equally spaced 0.030 in. (0.76 mm) diameter bleed holes, on the same axial centerlines as the bleed holes in the blade, were required on both sides of the leading and trailing edge plenum chambers. These could have been electro-discharge machined, however, it was found that high speed tool steel drill bits were adequate to do the job and were used for it. Figures 50 and 51 show the finned interior and flat exterior surfaces of the shells and a turbine blade after they were machined and ready to be activated diffusion brazed.

3.4.4 Activated Diffusion Brazing Trials

The initial concept for the fabrication of the finned shell blades was to simply activated diffusion braze the formed shells to the blades in a vacuum furnace using the pair of diffusion welding dies to apply the required pressure. The finned areas in contact with the blade on the pressure and suction faces were calculated to be 1.58 and 2.73 sq in. (10.2 and 17.6 sq cm), respectively, and a dead weight loading of approximately 35 lb (156 N) was necessary to produce the required 15 psi (103 KPa) loading determined in Tasks I and II. It was realized that the 35 lb (156 N) load was a compromise, however, since the contact areas were different and a direct loading could not be applied normal to the shell's surfaces because they were curved. This loading was considered adequate. The first attempt to activated diffusion braze the TDNiCr shells to a Rene' 80 blade was made with the first set of dies using the B-1 alloy in the form of transfer tape. The outside surfaces of both shells were lightly coated with a YO_2 stop-off compound to prevent bonding to the diffusion brazing dies. The components were assembled and placed in the vacuum brazing furnace with the dead weight load of 35 lb (156 N) placed on top. The assembly was activated diffusion brazed at 2230 ± 10°F (1743 ± 6 K)/25 min, the brazing cycle developed during Task I. The leading and trailing edges and tip caps were then joined to the component. After sectioning, it was determined that the stack-up of tolerances between the various components was too great to produce the required 90 percent fin contact area, although it was estimated that between 80 and 85 percent contact had been achieved.

The second trial was made in a vacuum hot press, whereby additional pressure could be applied to the dies. The first pair of dies was used again and a dead weight loading of 92 lb (409 N) was applied to them. As in the first trial, the B-1 alloy was applied to the blade in the form of transfer tape, and then activated diffusion brazed. After this activated diffusion braze run it was visually evident that the degree of vacuum obtained was not sufficient to permit the B-1 brazing alloy to flow properly. Consequently, a second activated diffusion brazing cycle was made using the same dead weight load of 35 lb (156 N) as used for the first trial. Sectioning of the blade showed the contact area to be essentially 100 percent, although the filleting of the diffusion weld was somewhat inferior due to the double brazing cycle.

The third trial was also made with the first set of dies. Due to the excellent contact area produced during the vacuum hot pressing cycle, it was decided to use the hot press to creep form the shells and blades prior to the activated diffusion brazing cycle. The entire blade and the outer surfaces of the shells were lightly coated with the YO_2 stop-off compound to prevent any diffusion brazing during the heating cycle. The components were assembled and loaded into the hot press and the same loading of 92 lb (409 N) was applied to them. They were heat treated at 2100°F (1422 K)/30 min in vacuum. No particular problems were encountered in disassembling the components and, as anticipated, an impression of the fins that were in contact with the blade remained in the stop-off compound on the blade. The stop-off compound was easily removed from the blade and finned area of the shells by lightly vapor honing with an air driven emulsion of Al_2O_3. The components were reassembled and were activated diffusion brazed. For this third trial the B-1 alloy was applied with the plasma spray process. The tolerance on the thickness was between 0.003 and 0.005 in. (0.08 and 0.13 mm) and was determined and maintained by spraying on a flat panel at the same time as the blade and measuring the thickness with a micrometer. The assembly was then sectioned to determine the quality of the activated diffusion brazes.

The fourth trial for the TDNiCr shells was made using the second set of dies which had become available. These are shown in Figure 52. Figure 53 shows a blade with the pressure and suction shells assembled in the dies.

Essentially the same creep forming and activated diffusion braze procedures as used for the third trial were used for the fourth trial. For this trial, the shells were gas-tungsten-arc tack welded to hold them in position prior to the assembly's insertion into the dies. These welds were broken loose after creep forming, however they provided locaters during the reassembly for activated diffusion brazing. The tack welds were in the tip cap area and were ground off after the blade was completely fabricated. Again, an excellent impression of the fin contact area was obtained on stop-off compound as illustrated in Figure 54.

The five bleed holes in the blade can be seen as well as the relationship of the edges of the fins forming the center plenum chambers on both shells. Figure 55 illustrates the intimate contact obtained at the leading edge area of the blade in contrast to the poor contact obtained when the first set of dies were used. By the time this last trial with the TDNiCr shells was completed, a number of bake-out cycles had been run on the vacuum hot press and the oxiditions encountered during the second trial had been eliminated. Consequently, the activated diffusion brazing cycle could have been combined with the creep forming cycle as was attempted in the second trial. However, the visual impressions on the stop-off compound provided an excellent means of evaluating the contact area that would be obtained during the activated diffusion brazing cycle. Therefore, it was considered a valuable non-destructive testing process and an important part of the overall fabricating procedure.

The creep forming of six pairs of TDNiCr shells for delivery to NASA was made before any attempts to creep form the trial U700 shells. After the six pairs of shells were formed, random cracking was noted in the welds that joined pairs of Rene' 80 blocks together that composed both the male and female dies. Rather than jeopardize the remainder of the program by continuing to work with them and possibly have the cracks get larger, the dies were returned to Danville Metals Inc. to be repair welded and have the airfoil contour reground. After their return, two trial creep forming cycles were made on pairs of U700 shells. The dead weight load of 92 lb (409 N) was applied; however, it was felt that a more reproducible loading, that could be achieved in other furnaces, was required. Consequently, a constant pressure of 1000 psi (6.89 MPa) was applied to the dies during the entire creep forming cycle. This adequately formed the shells, however it did not deform the fins. The contact areas of the fins in the "stop-off" compound were essentially 100 percent in both cases. The B-1 alloy for both these trials was applied by the plasma spray process. Figure 56 shows the pressure and suction surfaces of a Rene' 80 blade with the alloy applied. The plasma spray process was being evaluated as a method of applying the B-1 alloy because, as discussed in the Task I section of this report, the transfer tape manufacturer was having problems supplying "reproducible" transfer tape. Both of the assemblies were activated diffusion brazed at 2200 + 15°F/-0°F (1478 + 9 K/-0 K)/25 min using the same nominal 35 lb (156 N) loading as for the TDNiCr shells. After activated diffusion brazing, the assemblies were sectioned to determine the contact area and quality of the joints. As a result of the success and confidence level obtained by the creep forming and activated diffusion brazing operations on these two U700 assemblies and those on the TDNiCr assemblies, it was decided to embark immediately on producing the finished U700 - Rene' 80 blades for delivery to NASA.

3.4.5 Processing of Remaining Components

3.4.5.1 Leading Edges to Shells

As previously noted, the major effort of Task III was to be concentrated on the activated diffusion brazing of the fins to the blade. Consequently, straightforward approaches of joining the remainder of the components were evaluated. The electron beam and gas-tungsten-arc welding processes were used to weld the formed leading edges to the pressure and suction shells. The 45° bevel of the fins at this location provided a uniform transition from the leading edge to the finned shells and simplified their joining.

In cases where the fit-up was adequate for the electron-beam process, it was used. Conventional brazing would have been a good choice for the TDNiCr, however the closeness of the fins to the joint excluded this technique because there was considerable danger of the fin passages being clogged.

3.4.5.2 Shells to Platform

It was contemplated that the shells could be conventionally brazed to the blade platform at the same time as the tip caps and the trailing edge. Although times at temperature as short as 10 seconds were used, the Coast Metal 50 alloy (AMS4779) flowed into the first four bottom fins on both the pressure and suction shells. This was unacceptable and the gas-tungsten-arc welding process was used as an alternative. Hastelloy X was used as the filler metal and occasionally visual cracking was encountered in the weld metal. These cracks were repair welded.

3.4.5.3 Trailing Edges to Shells and Tip Caps to Blade

The joining of the tip cap to the blade and the trailing edge to the shells were obvious brazing applications and the Coast Metal No. 50 (AMS4779) alloy was used at both locations. They were brazed at the same time and the cycle used was 1950°F (1339 K)/2 min.

3.4.5.4 Heat Treatment

Considerable development work has been conducted on TDNiCr, U700, and Rene' 80 and it is known that U700 and Rene' 80 are sensitive to strain age cracking. This phenomenon can be alleviated in nickel base superalloys by welding in the solution treated condition followed by a high temperature stress relief or resolution treatment. Consequently, all welding was conducted after the shells had been activated diffusion brazed to the blade. All the components were in the solution treated condition prior to activated diffusion brazing. The activated diffusion brazing cycle did not appreciably alter this condition. This sequence was also compatible with the total heat treat cycle for the finned samples developed and tested in Tasks I and II. The brazing of the tip caps and trailing edges was conducted prior to the 1550°F (1116 K) aging cycle that was given to both material combinations. Inserting the brazing operation at this time insured that there would be no remelting of the activated diffusion brazing alloy, and no significant alteration of the total heat treat cycle. Listed below are the fabrication and heat treatment sequences used for both material combinations:

	TDNiCr - Rene' 80
Diffusion brazing temperature/time:	2230 ± 10°F (1494 ± 6 K)/25 min
Weld leading edge and shells to platform	
Post brazing heat treatments:	2000°F (1366 K)4 hr 1925°F (1325 K)/4 hr
Braze tip caps and trailing edge with AMS4779:	1957°F (1339 K)/2 min
Aging:	1550°F (1116 K)/16 hr

	U700 - Rene' 80
Diffusion brazing temperature/time:	2200 + 15°F (1478 + 9 K)/25 min - 0°F - 0 K
Weld leading edge and shells to platform	
Post brazing heat treatments:	1950°F (1339 K)/4 hr
Braze tip caps and trailing edge with AMS4779:	1950°F (1339 K)/2 min
Aging:	1550°F (1116 K)/24 hr 1400°F (1033 K)/16 hr

3.4.5.5 Metallographic Inspection

The four TDNiCr - Rene' 80 and two U700 - Rene' 80 diffusion brazed assemblies were sectioned and mounted for metallographic evaluation. In most cases, four radial cuts were made through the diffusion brazed area. Two of the three sections formed were mounted for transverse evaluation of the fin to blade joints. Axial sections were made through the remaining piece to provide longitudinal sections of the joint.

3.4.6 Fabrication of Blades for NASA

Six TDNiCr and six U700 finned shell blades were completely fabricated for delivery to NASA. They were made employing the techniques developed on the trial blades of each material combination as noted in the general outline listed below:

a. EDM fin contour on pressure and suction shell flats.
b. Die form pressure and suction shell flats and leading edge.
c. Trim and fit to "base dimension" blade and match to individual blade.
d. Machine trailing edge plenum chambers in pressure and suction face shells. Machine bleed hole in the leading edge plenum chamber area of pressure and suction shells and in the blade at the No. 4 radial hole.
e. Tack weld and assemble pressure and suction shells and blade in diffusion welding dies, and tack weld 80%Ni-20%Cr strips around dies to prevent any movement. Note: all contacting surfaces are to be coated with stop-off compound to prevent diffusion brazing during creep forming.
f. Load in vacuum hot press under constant pressure of 1000 psi (6.89 MPa), creep form at 2100°F (1422 K)/1.5 hr.
g. Disassemble and inspect for fin contact area on blade. Clean general fin to blade contact areas.
h. Mask blade in non-fin contact areas and plasma spray with B-1 alloy 0.003/0.005 in. (0.08/0.13 mm) thick on blade fin contact area.
i. Reassemble pressure and suction shells and blade in diffusion welding dies and tack weld 80%Ni-20%Cr strips around dies to prevent any movement. Note: Outer surface of pressure and suction shells to be coated with stop-off compound to prevent diffusion welding of shells to dies, due to possible overflow of B-1 alloy, during activated diffusion brazing cycle.
j. Load in vacuum furnace under dead weight loading of 35 lb (156 N), activated diffusion braze TDNiCr shells - Rene' 80 blade at 2230°F ± 10°F (1494 ± 6 K)/25 min and the U700 shells - Rene' 80 blade at 2200°F + 15°F and -0°F (1478 + 9 K and - 0 K)/25 min.
k. Disassemble and clean outer surfaces of shells being careful to prevent any clogging in the fin areas.
l. Fit and electron-beam or gas-tungsten-arc weld the leading edge to the pressure and suction shells.

m. Gas-tungsten-arc weld the shells to the blade using Hastelloy X filler metal.
n. Heat treat TDNiCr finned shell - Rene' 80 blades as follows: 2000°F (1366 K)/4 hr + 1925°F (1325 K)/4 hr + braze tip cap and trailing edge - 1950°F (1339 K)/2 min + 1550°F (1116 K)/16 hr.
o. Heat treat U700 finned shell blades as follows: 1950°F (1339 K) + braze tip cap and trailing edge - 1950°F (1339 K)/2 min + 1550°F (1116 K)/4 hr + 1400°F (1033 K)/16 hr.

3.4.7 Overall Evaluation of Results

Figure 57 illustrates the typical activated diffusion brazed filleting obtained at the leading edge area of the finned shells. This filleting was obtained when the B-1 alloy was either plasma sprayed or applied as transfer tape and then activated diffusion brazed. No passageway plugging was encountered on any of the trial TDNiCr finned shell - Rene' 80 blades, however, a few passageways were plugged on the two trial U700 finned shell - Rene' 80 blades. In one case the plugging was continued from the leading edge area to the center plenum chamber, however the remaining passageway plugging was approximately 0.060 in. (1.52 mm) in length, initiating at the leading edge of the finned shells. Three of the U700 finned shelled - Rene' 80 blades that were delivered to NASA contained a number of plugged passageways at the leading edge area of the pressure face shell, however their length was undeterminable. The possibility of repair activated diffusion brazing was not attempted because it was considered highly improbable that a rebrazing cycle could "unplug" the passageways. No plugging could be found at any of the leading edge areas of the TDNiCr suction face shells and none could be found in the leading or trailing edge area of the U700 pressure or suction face shells that were delivered to NASA.

Since non-destructive testing (NDT) development was not a portion of this work, no means (other than visual) were available to verify the quality of the joint or locate passageway plugging. The passageway plugging at the leading or trailing edge area could be located visually, however any unexposed plugging could not be easily seen. It is possible that radiographic techniques could have found the plugging, however it is improbable that it could determine joint quality. The passageway plugging was associated with the application of the B-1 alloy by plasma spraying. The blades that were furnished to NASA were plasma sprayed in sets of three and although similiar techniques were used to deposit the B-1 alloy, the three that contained the plugging were over sprayed on the pressure face. The pressure face is the difficult face to plasma spray because the operator has a tendency to hesitate while plasma spraying it and consequently deposits an excessive amount of alloy. Particular care was taken when spraying the second set of three blades and no hole clogging was encountered.

Figures 58 and 59 show the pressure and suction faces, respectively, of a completely fabricated blade. Smoke was introduced into the No. 4 radial hole and is shown exiting from the bleed holes, demonstrating that a complete path for its transmission had been produced. Figure 60 is a portion of a radial section through a completed blade, illustrating the contour of the fin area after activated diffusion brazing. The contact area for this section was essentially 100 percent, as was the case for the other sections that were made from trial pieces that had been creep formed prior to activated diffusion brazing. The filleting obtained was equivalent to that obtained in Tasks I and II. Figure 61 is an axial section through a finned area again illustrating the typical contact obtained along the length of the fins.

Figure 62 (top and bottom) shows photomicrographs of transverse sections through the fins of a TDNiCr finned shell blade. Figure 62 illustrates the cracking that was found in sections from all of the four TDNiCr trial activated diffusion brazed blades and also encountered in the cyclic exposed specimens tested for Task II. The cracks did not contain any oxide because of the vacuum environment in which the blades were activated diffusion brazed. Figure 63 is an axial section showing the cracking in a plane parallel to the fin's length. These sections were from the third trial activated diffusion braze that was made with plasma sprayed B-1 alloy, and since the blade was sectioned after activated diffusion brazing, the cracking must have occurred during the cooling portion of the single activated diffusion brazing cycle. Sufficient restraint and thermal shock must have been produced to generate the cracking, as was demonstrated in the thermally cycled samples of Task II. The severity of cracking found in transverse fin sections from the third trial was not as great as that found in sections from the second trial. Two activated diffusion brazing cycles were run on the second trial which would account for the increase in number and would corroborate the fact that the cracking is accumulative as demonstrated in Task II. In general, the cracking was confined to an area located approximately 0.75 in. (19 mm) above the platform section of the blade and was found in approximately 10 percent of the fins in this area. Evidently this area produced the highest degree of restraint, and hence the greatest amount of cracking. The lengths of the cracks varied and were difficult to evaluate since the relationship of the section to the overall crack length was not known, however simple measurements of a number of them from various sections indicated the longest to be approximately 0.030 in. (0.76 mm). In most cases, as shown in Figures 62 and 63, the cracking was well away from the activated diffusion brazed area, consequently they were not considered activated diffusion brazed defects, enabling the sections to meet the quality requirements of the program. Because of this, the six blades that were scheduled to be fabricated for NASA were completed. It is believed that the ribs contain cracks, the severity of which could have been increased due to the full heat treatment. Disregarding the fact that the defects were not in the activated diffusion brazed area, it is doubtful if they would have met the quality requirements since their closeness and accumulative lengths in some areas could have exceeded the 0.050 in. (1.27 mm) limit.

Figure 64 is a transverse section through the fins of a TDNiCr finned shell Rene' 80 blade that was activated diffusion brazed with plasma sprayed B-1 alloy. The activated diffusion brazes in Figure 64 can be compared with those in Figure 62 that were made with transfer tape. The improvement of the diffusion welds made with the plasma sprayed B-1 alloy is evident by absence of any void areas. The theorized reason for the void areas in the activated diffusion brazes made with the transfer tape was that they were due to the entrapment of gases produced by the volatile binder.

Figure 65 is a transverse section through the fins of a U700 finned shell blade. The B-1 alloy was applied by the plasma spray process. The quality of these diffusion brazes were comparable to those produced in the TDNiCr made using the plasma sprayed B-1 alloy.

The excellent contact area achieved on the blades that were furnished to NASA was due to the creep forming cycle imposed to match the finned shells to the blade. At times, after creep forming, slight indentations remained on the blade after the removal of the "stop-off" compound. These indentations appeared to be more prominent on the U700 finned shell - Rene' 80 blades than on the TDNiCr finned shell - Rene' 80 blades. Evidently, the creep strength of the U700 was less than that of the TDNiCr and consequently it was creep formed with less effort than the TDNiCr. One creep forming temperature was used for both material combinations and both operations were considered successful, however a slightly higher temperature might have made the TDNiCr shells move more easily.

The locations where the impressions in the "stop-off" compound were light or non-existent did not cause any difficulties because in all cases they were relatively small and the gap was estimated to be no greater than 0.002 in. (0.05 mm). Areas where there was a known gap were evaluated during the activated diffusion brazing trials and they were found to be adequately diffusion brazed. The gapping capabilities of the B-1 alloy were also demonstrated on flat samples in Task I. The thickness of the B-1 alloy was not taken into consideration during the creep forming operation, although the "stop-off" compound accounted for a finite thickness. Consequently, when it was added and 0.003/0.005 in. (0.08/0.13 mm) of B-1 alloy became molten during the activated diffusion brazing cycle, it would be forced into regions of mismatch.

In conclusion, the activated diffusion brazing process was shown to be applicable to complex turbine blades with twist, compound curvature, and variable chord width. Creep forming the finned shells to struts, in combination with precise preplacement of the brazing alloy, resulted in consistently sound joints, free of cooling passageway clogging.

4.0 DISCUSSION OF RESULTS

The results of this program, culminating with the production of eighteen full scale blades, demonstrated that the finned shell to strut blade can be reliably fabricated using the activated diffusion brazing process. The joining process was shown to be applicable to complex turbine blades with twist, compound curvature, and variable chord widths. It was demonstrated that airfoil shells with complex internal cooling passageways could be reliably joined to complex struts without damaging or obstructing the internal cooling configuration or other parts of the blade.

It was known at the outset of this program that at least two major problems needed to be surmounted for successful fabrication of the finned shell to strut blades:

1. Precise metering of brazing alloy to permit a sound joint without obstructing cooling passageways.
2. Close tolerance fit-up between the shell and strut in a complex blade shape.

Two techniques for precisely metering the powdered brazing alloy were successfully developed - preplacement by transfer tape and plasma spraying. Both techniques were successfully used throughout the program to produce sound joints, with generous fillets along each fin to strut juncture. When the amount of brazing alloy was precisely metered in location and amount, no cooling passageway or film cooling hole clogging was encountered. During the learning process of plasma spraying brazing alloy on the complex blade shapes, hole clogging was occasionally encountered. This was overcome by increased experience. The amount of experience gained in activated diffusion brazing several hundred finned test specimens and eighteen blades, conclusively demonstrated the reliability of the brazing alloy preplacement techniques.

The following is an overall comparison of the two preplacement techniques:

1. Transfer tape is an inexpensive, versatile means of precisely metering brazing alloy, but is sometimes of variable quality.
2. Plasma sprayed powders generally produce more sound joints (less voids), are of consistently high quality, but are more difficult to precisely meter. This limitation may become more severe with more complex joint configurations. Of course, plasma spraying facilities are required.

Each specific application must be evaluated to properly select preplacement technique. Both techniques worked well in this program.

The second major problem, close tolerance fit-up in complex blade shapes, was solved using conventional sheet metal forming processes to form the shell into the correct overall airfoil shapes. No unusual problems were encountered with forming finned shells of TDNiCr or U700. Creep forming was the coup de grace which precisely matched each shell with a strut. Once intimate contact between fins and strut was achieved, the same excellent joints which had been consistently produced with Task I and II specimens (where fit-up was no problem), were achieved with the complex blade shapes. Note particularly Figures 55, 57, and 60.

With respect to the metallurgical aspects of the activated diffusion brazed joints, the TDNiCr to Rene' 80 characteristics will be discussed first, followed by a discussion of the U700 to Rene' 80 joints.

Two shortcomings were revealed in the TDNiCr to Rene' 80 joints:

1. A weak zone immediately adjacent to the joint molten region.
2. Weak short transverse shear strength in TDNiCr sheet.

The weak zone adjacent to the joint molten region was detected by the TDNiCr to Rene' 80 butt joint specimens when tested in stress rupture. Although butt joint tensile efficiencies of greater than 90 percent were achieved, the stress rupture efficiency was approximately 30 percent. This demonstrates that tensile tests can be misleading and that stress rupture tests are more effective in detecting narrow weak regions transverse to the loading axis. The weak zone was found to be a combination of both ThO_2 agglomeration and depletion caused by diffusion of elements from the brazing alloy. Microprobe transverses confirmed that diffusion into the TDNiCr occurred during the activated diffusion brazing thermal cycle. The mechanism of the weak zone formation (diffusion) was further confirmed when degradation of the joint tensile properties occurred during thermal exposure. As shown in Figure 12, a 100 hr exposure at 1750°F (1228 K) sufficiently deteriorated the joint that even tensile properties were reduced (from approximately 90 to 60 percent efficiency).

Several attempts to reduce diffusion (hence, minimize the weak zone) such as nickel barrier and reduction in heat treatment were not sufficiently effective to significantly improve stress rupture efficiency (see Figure 13).

Although this weak zone could not be eliminated from the TDNiCr - Rene' 80 joints, the natural fillet formation along the fin to strut juncture restored joint integrity by placing the weak zone in a noncritical region. Extensive testing of finned joints, both tensile and rupture, in three directions, longitudinal, transverse, and short transverse clearly demonstrated that high joint integrity could consistently be achieved (note typical fin failures in Figures 10, 34, and 35). Even though high joint efficiencies were achieved (because of fillet reinforcement), a weakness was revealed in the TDNiCr short transverse (sheet thickness) direction. For example, 1750°F (1288 K) short transverse shear tensile strength was 40 percent of tensile strength in either longitudinal or transverse sheet directions.

Thermal cycling of simulated finned shell to strut specimens invariably resulted in cracking in the short transverse direction of the fins. Progression of cracking decreased with decreasing restraint and was accelerated by increased cyclic oxidation. Stress accelerated oxidation, akin to stress corrosion cracking, occurred in cyclic exposed specimens. The range of cracking encountered varied from severe, as shown in Figure 36 (high restraint, severe oxidation) to none, as shown in Figure 6 (low restraint, no oxidation). The restraint present in the blades apparently was intermediate between these extremes, and resulted in occasional slight cracking (see Figures 62 and 63).

Since some degree of cracking did occur in the short transverse direction of the fins, even in the blade configuration, this problem restricts the application of TDNiCr finned shells to struts. Judicious selection of both joint design (restraint) and thermal environment would be required to prevent such cracking. It may be possible to cast the fins on the strut, thus eliminating the TDNiCr in the fin portion of the blade.

High strength joints in U700 to Rene' 80 were achieved in both butt joint and finned shell to strut configurations. Butt joint tensile and stress rupture efficiencies greater than 60 percent were produced. All butt joint failures occurred in the activated diffusion brazed joint. Fin to strut joint test specimens, however, occasionally failed in the fins - indicating high joint efficiency. Again, the fin to strut joints were inherently reinforced by the braze fillets, which also reduced the stress concentrations. A high efficiency U700 to Rene' 80 joint resulted.

One apparent anomaly occurred during thermal exposure of U700 to Rene' 80 joints. Butt joints in Task I (Figure 23) increased in stress rupture strength after 100 hr at 1750°F (1228 K) exposure. This was attributed to the diffusion which occurred in the joint region. In contrast, the short transverse finned specimens in Task II decreased in rupture strength from approximately 100 to 65 percent efficiency after cyclic thermal exposure as shown in Figure 32.

Coating the short transverse finned specimens prevented oxidation from occurring during cyclic exposure but rupture properties remained low. The coated specimens had such a large weak diffusion zone that the expected improvement in stress rupture strength was negated.

5.0 CONCLUSIONS

Activated diffusion brazing parameters were developed and successfully applied to the fabrication of a finned shell to strut turbine blade. Both TDNiCr and U700 shells were joined to Rene' 80 struts. Extensive tensile and stress rupture testing critically assessed the joint quality and strength. The feasibility of fabrication of a finned shell to strut blade design was demonstrated by producing eighteen blades of this design.

During this work, several significant conclusions have been made.

1. Sound joints free from defects can consistently be produced in TDNiCr and U700 to Rene' 80 by the activated diffusion brazing process.
2. A weak zone was formed in the TDNiCr adjacent to the joint. This was attributed to thoria agglomeration.
3. The small fin passageways (0.025 x 0.028 in. (0.63 x 0.71 mm)) can consistently be electro-discharge machined to produce the finned shells.
4. Conventional sheet metal forming followed by creep forming the shells to struts will provide the close contact (within 0.003 in. (0.076 mm)) between fins and strut required for activated diffusion brazing.
5. Creep forming shells to struts, provides the intimate contact which is necessary in combination with precise preplacement of brazing alloy to consistently produce sound joints, free of passageway clogging in complex blade shapes.
6. Precise preplacement of brazing alloy can be accomplished with either transfer tape or plasma spraying.
7. Each fin to strut joint is contoured with a generous fillet, thereby reducing any stress concentration.
8. Butt joint tensile and stress rupture, finned shear joint tensile and stress rupture, and short transverse butt joint tensile and stress rupture testing revealed that adequate joint strengths can be achieved with both material combinations.
9. Thermal cycling of TDNiCr finned shells to Rene' 80 struts induced sufficient stresses to crack the fins in the short transverse direction. This limits either the restraint or thermal cycling severity to which finned TDNiCr - Rene' 80 struts can be subjected.
10. The U700 finned shells to Rene' 80 struts developed 100% joint efficiency and maintained 65% efficiency after thermal cycling.
11. Application of an oxidation resistant coating to the U700 to Rene' 80 finned specimens prevented oxidation but the presence of a weak diffusion zone resulted in 60% joint efficiency after cyclic exposure.
12. Base metal properties are retained during the activated diffusion brazing heat treatments.

6.0 RECOMMENDATIONS

This program demonstrated the feasibility of reliably activated diffusion brazing airfoil shells with complex internal cooling passageways to matching struts without damaging the cooling configuration or other parts of the blade. Following successful completion of this program, several processing steps must be defined to establish overall feasibility of the finned shell to strut blade. Although several areas of an advanced blade performance must be established, such as heat transfer characteristics, cooling passageway and film cooling hole optimization, etc., the following recommendations are confined to blade fabrication procedures.

1. Reliable, sensitive nondestructive inspection process(es) must be developed to detect both fin to strut joint quality and cooling passageway obstruction. Functional airflow tests, ultrasonic, and krypton inspection processes appear most applicable to a finned shell to strut blade design.

2. Reliable joining procedures must be established for the peripheral joining associated with the blade (tip cap attachment, trailing edge, and the shell to platform joints).

3. The concept of casting the finned passageways on the blade strut to negate the short transverse shear loading on the shell material fins should be evaluated.

4. Based on the relative ease of forming both TDNiCr and U700 airfoil shells in segments, forming of one piece airfoil shells should be no problem.

5. The ability of the finned shell to strut blade to resist thermal fatigue damage should be evaluated in either a cascade test or simulated thermal shock testing equipment. This would serve as a functional test of the fabricated blade integrity.

6. The substitution of advanced sheet alloys for TDNiCr and U700 should be evaluated. Advanced oxide dispersion strengthened alloys, such as FeCrAlY, NiCrAlY, or CoCrAlY are attractive candidates.

7.0 REFERENCES

1. Mechtly, E.A., "The International System of Units", Scientific and Technical Information Division, National Aeronautics and Space Administration, Washington, D.C. (1964).

2. Hoppin, G.S. and Berry T.F., "Activated Diffusion Bonding", Welding Journal Research Supplement, November, 1970.

3. Kelley, E.W., "Manufacturing Process for Improved High Strength Superalloy Sheet", Technical Report AFML-TR-69-114, June 1969.

TABLE I. CHEMICAL COMPOSITION OF MATERIALS USED

Material	(Weight Percent)														
	C	Mn	Si	P	S	Cr	Co	Ti	Mo	W	Al	B	Zr	Fe	ThO_2	Ni
Rene' 80 Specification	0.15-0.19	0.20 max.	0.20 max.	---	0.015 max.	13.70-14.30	9.00-10.00	4.80-5.20	3.70-4.30	3.70-4.30	2.80-3.20	0.1-0.2	0.03 0.04	0.20 max.	---	Balance
Rene' 80, 1/8 in. (3.2 mm) thick plate	0.26	0.01	0.034	---	0.005	13.42	9.99	5.20	3.93	3.79	2.65	0.017	0.03	0.14	---	Balance
TDNiCr Specification (B50TF46)	0.10 max.	---	---	---	0.03	19.0-23.0	0.3 max.	---	---	---	---	---	---	---	1.8-3.0	Balance
TDNiCr, Heat 3089	0.03	---	---	---	0.007	19.87	0.03	---	---	---	---	---	---	---	2.11	Balance
U700, Heat 8221-8-108	0.13	0.10	0.05	---	0.006	15.26	19.15	3.72	5.28	---	4.18	0.007	0.02	0.36	---	Balance
Brazing Alloy GE B-1 (Lot No. 244-59A)	0.18	0.08	5.31	<0.001	---	14.18	9.28	5.3	4.03	3.9	4.32	0.016	0.06	0.17	---	Balance
Brazing Alloy GE B-28 (Lot No. 244-59D)	0.18	0.12	0.91	0.003	---	14.50	9.05	5.04	4.00	4.18	3.82	2.13	0.03	1.20	---	Balance
Coast Metal 50	---	---	3.5	---	---	---	---	---	---	---	---	1.9	---	---	---	Balance

TABLE II. - ACCEPTANCE TESTING OF TDNiCr*

Heat 2996-2

All testing was conducted in the transverse direction.

All specimens were 0.050 in. thick with 1 in. long X 1/4 in. wide gage dimensions.

Tensile Properties

Test Temp (°F)	UTS (ksi)	0.2 YS (ksi)	El (%)
RT	135.0	103.0	15.0
RT	130.6	91.3	16.2
RT[a]	115.0	78.0	10.0
1750	28.5	---	1.9
1750	25.9	---	1.8
2000	18.9	18.9	2.5
2000	19.3	19.3	1.5
2000[a]	15.0	---	2.0

Stress-Rupture Properties

Test Temp (°F)	Stress (ksi)	Life (hr)	El (%)
1750	7.5	425.1	2.1
1750	10.0	28.8	3.0
2000	5.5	99.7	---
2000	5.5	111.6	---
2000	5.5	100.0	---
2000[a]	5.5	20.0	---

* These data are presented in Table II-A using SI units of measure.

[a] TDNiCr specification minimum.

TABLE II-A. - ACCEPTANCE TESTING OF TDNiCr

(Using SI Units of Measure)

Heat 2996-2

All testing was conducted in the transverse direction.

All specimens were 1.27 mm thick with 25.4 mm long X 6.4 mm wide gage dimensions.

Tensile Properties

Test Temp (K)	UTS (MPa)	0.2 YS (MPa)	El (%)
RT	931.0	710.0	15.0
RT	901.0	630.0	16.2
RT[a]	793.0	538.0	10.0
1228	197.0	---	1.9
1228	179.0	---	1.8
1366	130.0	130.0	2.5
1366	133.0	133.0	1.5
1366[a]	103.0	---	2.0

Stress-Rupture Properties

Test Temp (K)	Stress (MPa)	Life (hr)	El (%)
1228	52.0	425.1	2.1
1228	69.0	28.8	3.0
1366	38.0	99.7	---
1366	38.0	111.6	---
1366	38.0	100.0	---
1366[a]	38.0	20.0	---

[a] TDNiCr specification minimum.

TABLE III. - ACCEPTANCE TESTING OF U700*

Heat 8221-8-108

All specimens were 0.060 in. thick with 1 in. long by 1/4 in. wide gage dimension.

Tensile Properties						1750°F Stress-Rupture Properties			
Heat Treatment (a)	Test Temp (°F)	UTS (ksi)	0.2% YS (ksi)	El (%)		Heat Treatment (a)	Stress (ksi)	Life (hr)	El (%)
(1)	RT	196.8	122.1	23.2		(1)	23.0	11.6	13.4
(1)	RT	199.2	124.0	23.7		(1)	23.0	14.5	17.5
(2)	RT	141.8	129.5	1.8		(2)	15.0	134.1	4.3
(2)	RT	141.0	128.2	2.2		(2)	15.0	114.0	3.4
(1)	1750	56.4	46.8	11.8					
(1)	1750	60.8	49.0	13.6					
(2)	1750	63.5	54.5	10.7					
(2)	1750	69.7	60.9	10.3					

* These data are presented in Table III-A using SI units of measure.

a Heat Treatment (in vacuum)

(1) 2125°F/1/2 hr ; 1950°F/4 hr ; 1550°F/24 hr ; 1400°F/16 hr (conventional heat treatment).

(2) 2200°F/20 min ; 1950°F/4 hr ; 1550°F/24 hr ; 1400°F/16 hr (activated diffusion brazing thermal cycle).

TABLE III-A. - ACCEPTANCE TESTING OF U700*

(Using SI Units of Measure)

Heat 8221-8-108

All specimens were 1.52 mm thick with 25.4 mm long by 6.4 mm wide gage dimensions.

Tensile Properties						1228K Stress-Rupture Properties			
Heat Treatment (a)	Test Temp (K)	UTS (MPa)	0.2% YS (MPa)	El (%)		Heat Treatment (a)	Stress (MPa)	Life (hr)	El (%)
(1)	RT	1357	842	23.2		(1)	159	11.6	13.4
(1)	RT	1373	855	23.7		(1)	159	14.5	17.5
(2)	RT	978	893	1.8		(2)	103	134.1	4.3
(2)	RT	972	884	2.2		(2)	103	114.0	3.4
(1)	1228	389	323	11.8					
(1)	1228	419	338	13.6					
(2)	1228	438	376	10.7					
(2)	1228	481	420	10.3					

[a] Heat Treatment (in vacuum)

(1) 1436K/1/2 hr ; 1339K/4 hr ; 1116K/24 hr ; 1033K/16 hr (conventional heat treatment).

(2) 1478K/20 min ; 1339K/4 hr ; 1116K/24 hr ; 1033K/16 hr (activated diffusion brazing thermal cycle).

TABLE IV. - ACCEPTANCE TESTING OF RENE' 80

Heat VD-896

All specimens were heat treated in vacuum:2225°F/2 hr ; 2000°F/4 hr ; 1925°F/4 hr ; 1550°F/16 hr.

All specimens (except standard Rene' 80) were 0.100 in. thick with 1 in. long by 1/4 in. wide gage dimensions.

Tensile Properties			
Test Temp (°F)	UTS (ksi)	0.2 YS (ksi)	El (%)
RT	167.2	120.0	12.2
RT	168.2	115.8	14.2
RT[a]	135.0	114.0	6.5
1600	85.0	56.9	23.2
1600	88.7	71.1	19.0
1600[b]	90.0	70.0	---
1600[a]	100.0	76.0	10.5
1750	62.8	38.5	29.4
1750	55.6	34.9	28.8
1750	64.0	44.0	11.5

Stress-Rupture Properties			
Test Temp (°F)	Stress (ksi)	Life (hr)	El (%)
1750	27.5	21.5	5.5
1750	27.5	26.0	7.6
1800	27.5	7.0	9.0
1800	27.5	8.9	10.6
1800[b]	27.5	23.0	---

* These data are presented in Table IV-A using SI units of measure.

[a] Standard Rene' 80.

[b] Rene' 80 specification minimum.

TABLE IV-A. - ACCEPTANCE TESTING OF RENE' 80

(Using SI Units of Measure)

Heat VD-896

All specimens were heat treated in vacuum 1491K/2 hr; 1366K/4 hr; 1325K/4 hr; 1116K/16 hr.

All specimens (except standard Rene' 80) were 2.5 mm thick with 25.4 mm long by 6.4 mm wide gage dimensions.

Tensile Properties

Test Temp (K)	UTS (MPa)	0.2 YS (MPa)	El (%)
RT	1153	827	12.2
RT	1160	798	14.2
RT[a]	931	786	6.5
1144	586	392	23.2
1144	612	490	19.0
1144[b]	621	483	---
1144[b]	690	524	10.5
1228	433	266	29.4
1228	383	241	28.8
1228[a]	441	303	11.5

Stress-Rupture Properties

Test Temp (K)	Stress (MPa)	Life (hr)	El (%)
1228	190	21.5	5.5
1228	190	26.0	7.6
1255	190	7.0	9.0
1255	190	8.9	10.6
1255[a]	190	23.0	---

[a] Standard Rene' 80.

[b] Rene' 80 specification minimum.

TABLE V. EFFECT OF TRANSFER TAPE THICKNESS ON PASSAGE CLOGGING IN THE TDNiCr - RENE' 80 MATERIAL COMBINATION

Specimen No.	Brazing Alloy	Alloy Thickness (in.)	Alloy Thickness (mm)	Alloy Placement	Stop-Off	No. Fins	Passages Clogged
I-12	B-1	0.003	0.076	Bottom	No	12	0
I-13				Top	No	12	0
I-20-1				Bottom	Yes	3	0
I-21-1				Bottom	Yes	3	0
I-22-1				Bottom	Yes	5	0
23-1				Bottom	Yes	5	0
24-1				Bottom	Yes	7	0
25-1				Bottom	Yes	7	0
I-22	B-1	0.006	0.152	Top	No	12	Yes
I-23				Bottom	No	12	Yes
I-30				Top	No	12	0
I-31				Bottom	No	12	0
I-35				Top	Yes	12	0
I-36				Bottom	Yes	12	1
20				Bottom	No	3	1
20A				Bottom	No	3	1
21				Bottom	No	3	1
21A				Bottom	No	3	2
22				Bottom	No	5	2
23				Bottom	No	5	0
24				Bottom	No	7	0
25				Bottom	No	7	3
I-9	B-28	0.003	0.076	Bottom	No	12	0
I-10	B-28	0.003	0.076	Top	No	12	0
I-14	B-28	0.006	0.152	Bottom	No	12	0
I-15	B-28	0.006	0.152	Top	No	12	0

[a] Alloy Placement - with respect to fin postion.

TABLE VI. - OVERLAP SHEAR TENSILE STRENGTH OF FINNED TDNiCr ACTIVATED DIFFUSION BRAZED TO RENE' 80

Test specimens are shown in Figure 7.

Specimen No.	Fin Direction (a)	Shear Overlap No. Fins	Shear Overlap (in.)	Shear Overlap (mm)	TDNiCr Fins Ni-Plated	Test Temp (°F)	UTS (ksi)	Failure Location	Test Temp (K)	UTS (MPa)
T-109	11	---	0.25	6.3	Yes	RT	39.6	Joint	RT	273
T-110	11	---					39.1			270
T-114	11	---					28.7			198
						Average	35.8		Average	247
T-95	T	5	---	---	Yes	RT	36.0	Joint	RT	248
T-96	T	5	---	---			31.8			219
T-97	T	5	---	---			29.7			205
						Average	31.8		Average	226
T-115	11	---	0.25	6.3	Yes	1750	10.9	(b)	1228	75
T-116	11	---					12.3			85
T-117	11	---					8.8			61
T-111[c]	11	---					9.0			62
T-112[c]	11	---					9.6			66
						Average	10.1		Average	70
T-98	T	5	---	---	Yes	1750	11.3	Fins	1228	78
T-99	T	5	---	---			12.7			88
T-100	T	5	---	---			11.5			79
T-106[c]	T	5	---	---			11.6			80
T-107[c]	T	5	---	---			10.1			70
						Average	11.4		Average	79

TABLE VI. - (CONCLUDED)

Specimen No.	Fin Direction (a)	Shear Overlap No. Fins	(in.)	(mm)	TDNiCr Fins Ni-Plated	Test Temp (°F)	UTS (ksi)	Failure Location	Test Temp (k)	UTS (MPa)
OL-20	T	3	---	---	No	1750	12.0	Fins	1228	83
OL-21	T	5	---	---			11.8			81
OL-22	T	5	---	---			9.7			67
OL-23	T	5	---	---			7.0			48
OL-24	T	7	---	---			11.0			76
OL-25	T	7	---	---			10.1			70
						Average	$\boxed{10.3}$		Average	$\boxed{71}$
PM[d]	---	---	---	---	---	1750	11.6	---	1228	80
PM[d]	---	---	---	---	---		11.8	---		81
PM[d]	---	---	---	---	---		11.1	---		77
PM[d]	---	---	---	---	---		11.3	---		78
						Average	$\boxed{11.4}$		Average	$\boxed{79}$

a Fin Direction: T = Fins perpendicular to load axis;
11 = Fins parallel to load axis.

b Specimen failed in parent metal finned section adjacent to overlap area.

c Specimen had a 0.002 in. (0.05 mm) joint gap.

d PM = Parent Metal shear specimen (see Figure 7).

TABLE VII. - 1750°F (1228K) SHEAR STRESS RUPTURE STRENGTH OF FINNED TDNiCr ACTIVATED DIFFUSION BRAZED TO RENE' 80

Test specimen is shown in Figure 7.

Specimen No.	Fin Direction (a)	Shear Overlap No. Fins	Shear Overlap (in.)	Shear Overlap (mm)	TDNiCr Fins Ni-Plated	Stress (ksi)	Life (hr)	Failure Location	Stress (MPa)
T-101	T	5	---	---	Yes	5.0	0.3	Fins	35
T 104	T	5	---	---	Yes	4.0	21.1	↓	28
T-103	T	5	---	---	Yes	3.5	42.9	↓	24
T-126	T	5	---	---	No	3.5	90.4	↓	24
T-108[b]	T	5	---	---	Yes	3.0	13.5	↓	21
T-102	T	5	---	---	Yes	3.0	185.4	↓	21
PM[c]	T	---	---	---	---	4.0	400[d]	---	28
T-122	11	---	0.25	6.3	Yes	5.0	0.1[e]	None	35
T-124	11	---	↓	↓	No	3.5	382+[d]	↓	24
T-113[b]	11	---	↓	↓	Yes	3.0	27.7[e]	↓	21
T-123	11	---	↓	↓	Yes	3.0	526+[d]	↓	21

a Fin Direction: T = Fins perpendicular to load axis;
11 = Fins parallel to load axis.

b Specimen had a 0.002 in. (0.05 mm) joint gap.

c PM = Parent Metal shear specimen.

d Test was terminated without failure.

e Pin failure occurred.

TABLE VIII. - 1750°F (1228K) BUTT JOINT TENSILE PROPERTIES OF TDNiCr ACTIVATED DIFFUSION BRAZED TO RENE' 80

Test specimen is shown in Figure 11.

Specimen No.	Rene' 80 Heat Treated (a)	TDNiCr Ni-Plated	Exposure (b)	UTS (ksi)	El (%)	Failure Location	UTS (MPa)
T-7	No	No	No	28.8	---	Joint	199
T-8	Yes			47.3[c]	1.5	TDNiCr[d]	(c)
T-9	Yes			25.6	---	Joint	177
T-10	Yes			24.4	1.06	TDNiCr[d]	168
			Average	26.6		Average	183
T-2	No	No	Yes	15.6	0.7	Joint	108
T-3				18.2	0.7		126
T-5				16.8	---		116
			Average	16.9		Average	117
T-13	Yes	Yes	No	16.6	0.14	Joint	115
T-14				23.7	0.28		163
T-15				20.0	0.28		138
T-25				21.5	---		148
			Average	20.5		Average	141

TABLE VIII. - (CONCLUDED)

Specimen No.	Rene' 80 Heat Treated (a)	TDNiCr Ni-Plated	Exposure (b)	UTS (ksi)	El (%)	Failure Location	UTS (MPa)
T-19	Yes	Yes	Yes	15.8	---	Joint	109
T-20	↓	↓	↓	17.1	0.07	↓	118
T-21				14.3	---		99
			Average	$\boxed{15.7}$		Average	$\boxed{108}$

a Rene' 80 Heat Treated: Prior to the activated diffusion brazing cycle; 2225°F (1491K)/ 2 hr.

b Exposure: 1750°F (1228K)/ 100 hr in air prior to testing.

c The value of the load was reported too high, therefore, the indicated stress was not used in the average.

d TDNiCr = Failure occurred in the TDNiCr immediately adjacent to the molten zone.

TABLE IX. - 1750°F (1228K) BUTT JOINT STRESS RUPTURE PROPERTIES OF TDNiCr ACTIVATED DIFFUSION BRAZED TO RENE' 80

Test specimen is shown in Figure 11.

Specimen No.	TDNiCr Ni Plated	Exposure (a)	Stress (ksi)	Life (hr)	Failure Location	Stress (MPa)
T-1	No	No	4.0	6.2[b]	Joint	28
T-6	No	No	4.0	2.1[b]	Joint	28
T-11	No	No	5.0	51.5	Joint	36
T-12	↓	↓	5.0	20.6	↓	36
T-31			4.0	13.4		28
T-32			4.0	2.3		28
T-34			3.0	43.5		21
T-16	Yes	No	4.0	6.2	Joint	28
T-17	↓	↓	4.0	0.1[c]	↓	28
T-18			5.0	1.5		36
T-24			3.0	74.0		21
T-26			3.0	54.2		21
T-27			3.0	452[d]		21
T-28	No	Yes	4.0	7.3	Joint	28
T-29	↓	↓	3.0	84.0	↓	21
T-30			3.0	32.3		21
T-22	Yes	Yes	3.0	1.4	Joint	21
T-23	Yes	Yes	3.0	4.9	Joint	21
T-33	No	No	4.0	14.2[e]	Joint	28
T-35	↓	↓	3.0	21.0[e]	↓	21
T-36			3.0	51.4[e]		21

[a] Exposure: 1750°F (1228K)/100 hr in air prior to testing.

[b] Inferior results occurred because the Rene'80 used for these specimens did not receive the standard 2225°F (1491K)/2 hr heat treatment prior to brazing.

[c] Specimen was aligned improperly.

[d] Test was terminated without failure.

[e] Specimens were not heat treated after activated diffusion brazing.

TABLE X. - EFFECT OF TRANSFER TAPE THICKNESS ON PASSAGE CLOGGING IN THE U700 - RENE 80 MATERIAL COMBINATION

Specimen No.	Brazing Alloy	Alloy Thickness (in.)	Alloy Thickness (mm)	Alloy Pre-Placement (a)	Stop-Off Used	No. Fins	Passages Clogged
I-16	B-1	0.003	0.076	Top	No	12	0
I-17	↓	↓	↓	Bottom	No	12	0
26-1	↓	↓	↓	Bottom	Yes	3	0
27-1	↓	↓	↓	Bottom	Yes	3	0
28-1	↓	↓	↓	Bottom	Yes	5	0
29-1	↓	↓	↓	Bottom	Yes	5	0
30-1	↓	↓	↓	Bottom	Yes	7	0
31-1	↓	↓	↓	Bottom	Yes	7	0
I-28	B-1	0.006	0.152	Top	No	12	5
I-29	↓	↓	↓	Bottom	No	12	7
I-32	↓	↓	↓	Top	Yes	12	0
I-33	↓	↓	↓	Top	Yes	12	0
I-34	↓	↓	↓	Bottom	Yes	12	3
26A	↓	↓	↓	Bottom	No	3	0
27A	↓	↓	↓	Bottom	No	3	0
I-18	B-28	0.003	0.076	Top	No	12	1
I-19	B-28	0.003	0.076	Bottom	No	12	0
I-1	B-28	0.006	0.152	Top	No	12	Several
I-2	↓	↓	↓	Top	Yes	12	0
I-20	↓	↓	↓	Top	No	12	Several
I-21	↓	↓	↓	Bottom	No	12	Several
I-26	↓	↓	↓	Top	No	12	1
I-27	↓	↓	↓	Bottom	No	12	1
26	↓	↓	↓	Bottom	No	3	0
27	↓	↓	↓	Bottom	No	3	0
28	↓	↓	↓	Bottom	No	5	0
29	↓	↓	↓	Bottom	No	5	0
30	↓	↓	↓	Bottom	No	7	1
31	↓	↓	↓	Bottom	No	7	0

[a] Alloy Preplacement - with respect to fin position.

TABLE XI. - OVERLAP SHEAR TENSILE STRENGTH OF FINNED U700 ACTIVATED DIFFUSION BRAZED TO RENE' 80

Test specimen is shown in Figure 7.

Specimen No.	Fin Direction (a)	Shear Overlap			Test Temp (°F)	UTS (ksi)	Failure Location	Test Temp (K)	UTS (MPa)
		No. Fins	(in.)	(mm)					
U-76	11	---	0.25	6.3	RT	23.5	Joint	RT	162
U-77	11	---	↓	↓	↓	34.9	↓	↓	241
U-78	11	---				29.6			204
					Average	29.3		Average	202
U-62	T	5	---	---	RT	32.8	Joint	RT	226
U-65	T	5	---	---	↓	33.5	↓	↓	231
U-67	T	5	---	---		31.8			219
					Average	32.4		Average	223
U-79	11	---	0.25	6.3	1750	34.2	Joint	1228	236
U-80	11	---	↓	↓	↓	30.6	(b)	↓	211
U-81	11	---				35.4	(b)		244
					Average	33.4		Average	230
U-90	11	---	0.25	6.3	1750	18.5	(b)	1228	128
U-91	11	---	0.25	6.3	1750	23.7	Joint	1228	163
					Average	21.1		Average	146

TABLE XI. - (CONCLUDED)

Specimen No.	Fin Direction (a)	Shear Overlap No. Fins	Shear Overlap (in.)	Shear Overlap (mm)	Test Temp (°F)	UTS (ksi)	Failure Location	Test Temp (K)	UTS (MPa)
U-68	T	5	---	---	1750	11.5	Joint	1228	80
U-69	T	5	---	---	↓	26.5	↓	↓	183
U-70	T	5	---	---	↓	25.2	↓	↓	174
					Average	21.1		Average	146
U-92[c]	T	5	---	---	1750	20.1	Joint	1228	139
U-93[c]	T	5	---	---	1750	18.2	Joint	1228	126
					Average	19.2		Average	132
OL-26[d]	T	3	---	---	1750	23.0	Joint	1228	159
OL-28[d]	T	5	---	---	↓	13.0	↓	↓	90
OL-29[d]	T	5	---	---	↓	15.2	↓	↓	105
OL-31[d]	T	7	---	---	↓	12.4	↓	↓	86
					Average	15.9		Average	110

[a] Fin Direction: T = Fins perpendicular to load axis;
11 = Fins parallel to load axis.

[b] Pin failure occurred.

[c] Specimen had a 0.002 in (0.05 mm) joint gap.

[d] Specimen had a gage section reduced to 1/2 in. (12.7 mm) wide.

TABLE XII. - 1750°F (1228K) SHEAR STRESS RUPTURE STRENGTH OF FINNED U700 ACTIVATED DIFFUSION BRAZED TO RENE' 80

Test specimen is shown in Figure 7.

Specimen No.	Fin Direction (a)	Shear Overlap			Stress (ksi)	Life (hr)	Failure Location	Stress (MPa)
		No. Fins	(in.)	(mm)				
U-82	11	---	0.25	6.3	15.0	0.1	Pin	103
U-83	11	---			12.0	0.1	Joint	103
U-84	11	---			12.0	0.1	Joint	103
U-88	11	---			12.0	0.1	Pin	103
U-85	11	---			10.0	0.1	Joint	103
U-86	11	---			10.0	30.9	Pin	69
U-71	T	5	---	---	15.0	3.3	Joint	103
U-72	T	5	---	---	15.0	3.3	Joint	103
U-73	T	5	---	---	15.0	3.3	Joint	103
U-75	T	5	---	---	15.0	3.3	Joint	103
U-74	T	5	---	---	15.0	3.3	Joint	103
U-63	T	5	---	---	8.0	145.5	Pin	103

a Fin Direction: T = Fins perpendicular to load axis;
11 = Fins parallel to load axis.

b Pin failure occurred.

TABLE XIII. - 1750°F (1228K) BUTT JOINT TENSILE PROPERTIES OF U700 ACTIVATED DIFFUSION BRAZED TO RENE' 80

Test specimen is shown in Figure 11.

Specimen No.	Exposure (a)	UTS (ksi)	0.2% YS (ksi)	El (%)	Failure Location	UTS (MPa)	0.2% YS (MPa)
U-1	No	50.0	47.8	0.34	Joint	345	330
U-2	↓	44.6	42.4	0.28	↓	308	292
U-3	↓	55.8	50.0	0.62	↓	335	345
	Average	50.1	46.7	0.41		345	322
U-7	Yes	50.6	42.2	0.56	Joint	349	291
U-9	↓	38.2	----	0.07	↓	263	---
U-10	↓	55.6	43.8	0.84	↓	383	302
	Average	48.1	----	0.49		332	---

[a] Exposure: 1750°F (1228K)/100 hr prior to testing.

TABLE XIV. - 1750°F (1228K) BUTT JOINT STRESS RUPTURE PROPERTIES OF U700 ACTIVATED DIFFUSION BRAZED TO RENE' 80

Specimen No.	Exposure (a)	Stress (ksi)	Life (hr)	Failure Location	Stress (MPa)
U-4	No	15	8.5	Joint	103
U-5	↓	12	45.0	↓	83
U-6	↓	10	63.5	↓	69
U-13	↓	10	30.1	↓	69
U-12	Yes	12	53.0	Joint	83
U-15	↓	12	68.8	↓	83
U-11	↓	10	116.8	↓	69
U-14	↓	10	211.0	↓	69

[a] Exposure: 1750°F (1228K)/100 hr in air prior to testing.

TABLE XV. - VARIATION OF JOINT CONFIGURATION OF TASK II SHORT TRANSVERSE FINNED SPECIMENS

Evaluation of joint configuration was done by 1750°F (1228K) tensile testing.

Only the TDNiCr - Rene' 80 short transverse finned specimens were used for this evaluation.

Specimen No.	UTS (a) (ksi)	UTS (a) (MPa)	Joint Configuration	Location of Failure
T-1	8.8	61	Rene' 80 - transfer tape - flat surface - fins down - transfer tape - Rene' 80.	Between the flat TDNiCr surface and Rene' 80 flat surface.
T-2	1.4	10	Rene'80 - transfer tape - fins up - flat surface - 2 layers transfer tapes - slotted Rene'80.	Between the flat TDNiCr surface and the slotted Rene' 80.
T-3	2.2	15	Rene' 80 - transfer tape - fins up - flat surface - 2 layers transfer tapes - cross-slotted Rene' 80.	Between the flat TDNiCr surface and the cross-slotted Rene' 80.
T-4	N/R[b]	N/R[b]	Rene' 80 - transfer tape - fins up - flat surface - 2 layers transfer tapes - flat surface - fins down - transfer tape - Rene' 80.	Between the two flat TDNiCr surfaces.
T-5	N/R[b]	N/R[b]	Rene' 80 - transfer tape - fins up - flat surface - 2 layers transfer tapes - flat surface - fins down - transfer tape - Rene' 80.	Between the two flat TDNiCr surfaces.
T-6	4.8	33	Rene' 80 - sintered transfer tape - remachined flat surface - (TDNiCr wafer previously brazed to Rene' 80 with fins down).	Between the flat TDNiCr surface and the flat Rene' 80 surface.

TABLE XV. - (CONTINUED)

Specimen No.	UTS (a) (ksi)	UTS (a) (MPa)	Joint Configuration	Location of Failure
T-7	68	9.8	Rene' 80 - sintered transfer tape - shallow fins - (TDNiCr wafer previously brazed to Rene' 80 with fins down).	Between shallow fins of the TDNiCr wafer and the Rene' 80 flat surface.
T-8	3	0.4	(Rene' 80 - with TDNiCr wafer previously brazed with fins up) - shallow fins down - transfer tape - sintered transfer tape - Rene' 80.	Between shallow fins of the TDNiCr wafer and the Rene' 80 flat surface.
T-9	72	10.5	Rene' 80 - transfer tape - fins up - shallow fins down - 2 layers transfer tapes - Rene' 80.	Fin failures.
T-10	55	8.0	Rene' 80 - transfer tape - fins up - shallow fins down - 2 layers transfer tapes - Rene' 80.	Between the TDNiCr shallow fins and the Rene' 80 flat surface.
T-11	73	10.6	Rene' 80 - transfer tape - fins up - shallow fins down - plasma sprayed Rene' 80.	Fin failure.
T-12	46	6.6	Rene' 80 - transfer tape - fins up - plasma sprayed shallow fins - Rene' 80.	Fin failures - however some areas were unbrazed.
T-13	78	11.3	Plasma sprayed Rene' 80 - fins up - shallow fins down - plasma sprayed Rene' 80.	Fin failure.

TABLE XV. - (CONCLUDED)

Specimen No.	UTS (a) (ksi)	UTS (a) (MPa)	Joint Configuration	Location of Failure
T-14	18	2.6	Rene' 80 - plasma sprayed fins up - plasma sprayed shallow fins down - Rene' 80.	Between the TDNiCr shallow fins and the Rene' 80 flat surface.

[a] The UTS reported is the maximum stress reached if failure of the standard fins did not occur.

[b] N/R = No value was reported; test was unsuccessful.

TABLE XVI. - HEAT TREATMENT FOR THE TASK II SHORT TRANSVERSE FINNED SPECIMENS

Material	Temp (°F)	Temp (K)	Time (hr)	Type Cycle	Remarks
Rene' 80	2225	1491	2	Solution	Rene' 80 clevis blocks only.
TDNiCr Rene' 80	2200^{+15}_{-0}	1478^{+9}_{-0}	(25 min)	Braze	Activated diffusion brazing cycle. Heat-up rate of 20°F (11K)/min.
	2000	1336	4	Overage	---
	1925	1325	4	Coating	No actual coating was used.
	1550	1116	16	Age	---
	1750[a]	1228	200	Exposure	Thirteen thermal cycles.
U700-Rene' 80	2200^{+15}_{-0}	1478^{+9}_{-0}	(25 min)	Braze	Activated diffusion brazing cycle. Heat-up rate of 20°F (11K)/min.
	1950	1339	4	Overage	If a coating cycle was used the temperature was 1925°F (1325 K).
	1550	1116	24	Age	---
	1400	1033	16	Age	---
	1750[a]	1228	200	Exposure	Thirteen thermal cycles.

[a] Cyclic exposure given to some specimens to study the effects of thermal cycling.

TABLE XVII. - SHORT TRANSVERSE TENSILE PROPERTIES OF FINNED TDNiCr ACTIVATED DIFFUSION BRAZED TO RENE' 80

Test specimen is shown in Figure 24.

Specimen No.	Thermal Cyclic Exposure (a)	Test Temp (°F)	UTS (ksi)	Failure Location	Test Temp (K)	UTS (MPa)
T-15	No	RT	61.4	(b)	RT	423
T-18	↓	↓	72.0	(b)	↓	496
T-19	↓	↓	61.4	Fins	↓	423
		Average	64.9		Average	448
T-17	Yes	RT	6.9	Joint	RT	48
T-24	↓	↓	11.6	Combination[c]	↓	80
T-26	↓	↓	14.9	Combination[c]	↓	103
		Average	11.1		Average	77
T-41[d]	Yes	RT	22.4	Fins	RT	154
T-42[d]	Yes	RT	26.9	Fins	RT	186
		Average	24.6		Average	170
T-39[e]	Yes	RT	40.3	Fins	RT	278
T-40[e]	Yes	RT	44.4	Fins	RT	306
		Average	42.3		Average	292
T-9	No	1750	10.5	Fins	1228	72
T-11	↓	↓	10.6	↓	↓	73
T-13	↓	↓	11.3	↓	↓	78
		Average	11.3		Average	75

TABLE XVII. - (CONCLUDED)

Specimen No.	Thermal Cyclic Exposure (a)	Test Temp (°F)	UTS (ksi)	Failure Location	Test Temp (K)	UTS (MPa)
T-16	Yes	1750	5.7	Joint	1228	39
T-20	Yes	1750	4.2	Joint	1228	29
		Average	4.9		Average	24

[a] Thermal Cyclic Exposure: Specimen was exposed for 13 thermal cycles at 1750°F (1228K) for 200 hr prior to testing.

[b] Failure occurred between the shallow TDNiCr fins and the Rene' 80.

[c] Combination failure = Failure occurred both at the joint and in the fins.

[d] For these specimens, the finned TDNiCr wafer was joined to just one Rene' 80 clevis block during thermal cyclic exposure.

[e] For these specimens the finned TDNiCr wafer was joined to a 0.100 (2.54 mm) Rene' 80 wafer during thermal cyclic exposure.

TABLE XVIII. - SHORT TRANSVERSE STRESS RUPTURE PROPERTIES OF FINNED TDNiCr ACTIVATED DIFFUSION BRAZED TO RENE' 80

Test specimen is shown in Figure 24.

Specimen No.	Test Temp (°F)	Stress (ksi)	Life (hr)	Failure Location	Test Temp (K)	Stress (MPa)
T-35	1600	7.0	2.6	Combination[a]	1144	48
T-38	↓	6.0	12.9	Fins	↓	41
T-50	↓	6.0	162+	(b)	↓	41
T-33	↓	5.0	9.4	Joint	↓	35
T-49	↓	5.0	306+	(b)	↓	35
T-23	↓	5.0	959+	(b)	↓	35
T-22[c]	1750	5.0	1.7	Fins	1228	35
T-28	↓	4.0	1.2	Fins	↓	28
T-21	↓	4.0	782+	(b)	↓	28
T-29	↓	3.0	14.8	Fins	↓	21
T-30	↓	3.0	14.8	Fins	↓	21
T-32	↓	3.0	36.6	Fins	↓	21
T-51	↓	2.5	258+	(b)	↓	17
T-31	1900	2.0	17.2	Fins	1311	14
T-34	↓	1.5	31.4	Fins	↓	10
T-36	↓	1.5	89.0	Fins	↓	10
T-27	↓	1.5	156.0	Joint	↓	10
T-37	↓	1.3	169.0	Fins	↓	9

[a] Combination failure = Failure occurred both at the joint and in the fins.

[b] Test was terminated without failure.

[c] One passageway was clogged.

TABLE XIX. - SHORT TRANSVERSE TENSILE PROPERTIES OF FINNED U700 ACTIVATED DIFFUSION BRAZED TO RENE' 80

Test specimen is shown in Figure 24.

Specimen No.	Thermal Cyclic Exposure (a)	Test Temp (°F)	UTS (ksi)	Failure Location	Test Temp (K)	UTS (MPa)
U-4	No	RT	53.4	Joint	RT	368
U-9	↓	↓	59.6	↓	↓	411
U-16			33.3			230
U-36			46.7			322
U-37			51.0			352
		Average	48.8		Average	357
U-5	Yes	RT	51.8	Combination[b]	RT	357
U-23	Yes	RT	49.4	Joint	RT	341
		Average	50.6		Average	349
U-17	Yes	RT	33.1[c]	Joint	RT	228
U-18	Yes	RT	39.0[c]	Joint	RT	267
		Average	36.0		Average	247
U-3	No	1750	25.6[d]	Combination[b]	1228	177
U-7	↓	↓	45.6	Pin	↓	314
U-8			44.4	Pin		306
		Average	38.5		Average	265
U-6	Yes	1750	39.6	Joint	1228	273
U-19			36.4			251
U-20			42.5			293
		Average	39.5		Average	272

See footnotes a thru d on next page.

TABLE XIX. - (CONCLUDED)

[a] Thermal cyclic exposure: Specimen was exposed for 13 thermal cycles at 1750°F (1228K) for 200 hr prior to testing.

[b] Combination failure = Failure occurred both at the joint and in the fins.

[c] Specimens had 1/2 in. (13 mm) round oxidized area in center of finned joint failure; contamination prior to brazing was suspect.

[d] An initial attempt to test this specimen resulted in a pin failure which might have led to the low UTS of the second test.

TABLE XX. - SHORT TRANSVERSE STRESS RUPTURE PROPERTIES OF FINNED U700 ACTIVATED DIFFUSION BRAZED TO RENE' 80

Test specimen is shown in Figure 24.
C-1 through C-7 are coated U700-Rene' 80 specimens.

Specimen No.	Thermal Cyclic Exposure (a)	Test Temp (°F)	Stress (ksi)	Life (hr)	Failure Location	Test Temp (K)	Stress (MPa)
U-29	No	1600	35.0	27.1	Joint	1144	241
U-35	↓	↓	32.0	45.7	Joint	↓	221
U-26	↓	↓	30.0	55.9	(b)	↓	207
U-43	↓	↓	28.0	182+	(c)	↓	193
U-33	↓	↓	25.0	103.3	Joint	↓	172
U-45	Yes	1600	30.0	F.O.L.[d]	Joint	1144	207
U-48	↓	↓	25.0	↓	↓	↓	172
U-55	↓	↓	20.0	↓	↓	↓	138
U-66	Yes	1600	30.0	61.8[e]	Combination[f]	1144	207
U-65	↓	↓	30.0	66.0	↓	↓	207
U-61	↓	↓	22.0	35.9	↓	↓	152
U-59	↓	↓	20.0	52.1	↓	↓	138
U-60	↓	↓	18.0	158.6	↓	↓	124
U-58	↓	↓	18.0	185+	(c)	↓	124
U-13	No	1750	20.0	0.8	Joint	1228	138
U-27	↓	↓	18.0	59.3	Joint	↓	124
U-26	↓	↓	18.0	65.9	(b)	↓	124
U-12	↓	↓	18.0	161.4	Joint	↓	124
U-64	↓	↓	16.0	127.6	Joint	↓	110
U-11	↓	↓	15.0	207.9	Joint	↓	103
U-21	Yes	1750	18.0	8.9	Joint	1228	124
U-22	↓	↓	15.0	15.6	Joint	↓	103
U-52	↓	↓	12.0	6.5	(f)	↓	83
U-56	↓	↓	12.0	71.9	Joint	↓	83
U-46	↓	↓	10.0	54.8	(f)	↓	69
U-53	↓	↓	8.0	208+	(c)	↓	55

TABLE XX. - (CONCLUDED)

Specimen No.	Thermal Cyclic Exposure (a)	Test Temp (°F)	Stress (ksi)	Life (hr)	Failure Location	Test Temp (K)	Stress (MPa)
C-6	Yes[g]	1750	18.0	3.4[h]	Joint	1228	124
C-1			18.0	6.6			124
C-3			16.0	2.4			110
C-2			16.0	12.6			110
C-4			14.0	11.3			96
C-5			12.0	36.7			83
C-7			12.0	16.0[i]	None		83
U- 4	No	1900	10.0	1.0	Joint	1311	69
U-25			7.0	11.7	Joint		48
U-34			6.0	56.0	Joint		48
U-30			6.0	62.1	(f)		41
U-28			5.0	95.1	(f)		35
U-49	Yes	1900	6.0	23.1	(f)	1311	41
U-47			5.0	47.8			35
U-44			5.0	53.8			35
U-54			4.0	85.8			28

a Thermal cyclic exposure: Specimen was exposed for 13 thermal cycles at 1750°F (1228K) for 200 hr prior to testing.

b Failure occurred between the shallow U700 fins and the Rene' 80 clevis block.

c Test was terminated without failure.

d Specimens failed on loading due to severe loading rates.

e Specimen was loaded slowly.

f Combination failure = Failure occurred both at the joint and in the fins.

g Specimen was given a coating cycle after brazing.

h Specimen was given a solution heat treatment after thermal cycling.

i Specimen was not tested to failure, metallographic mounts were made.

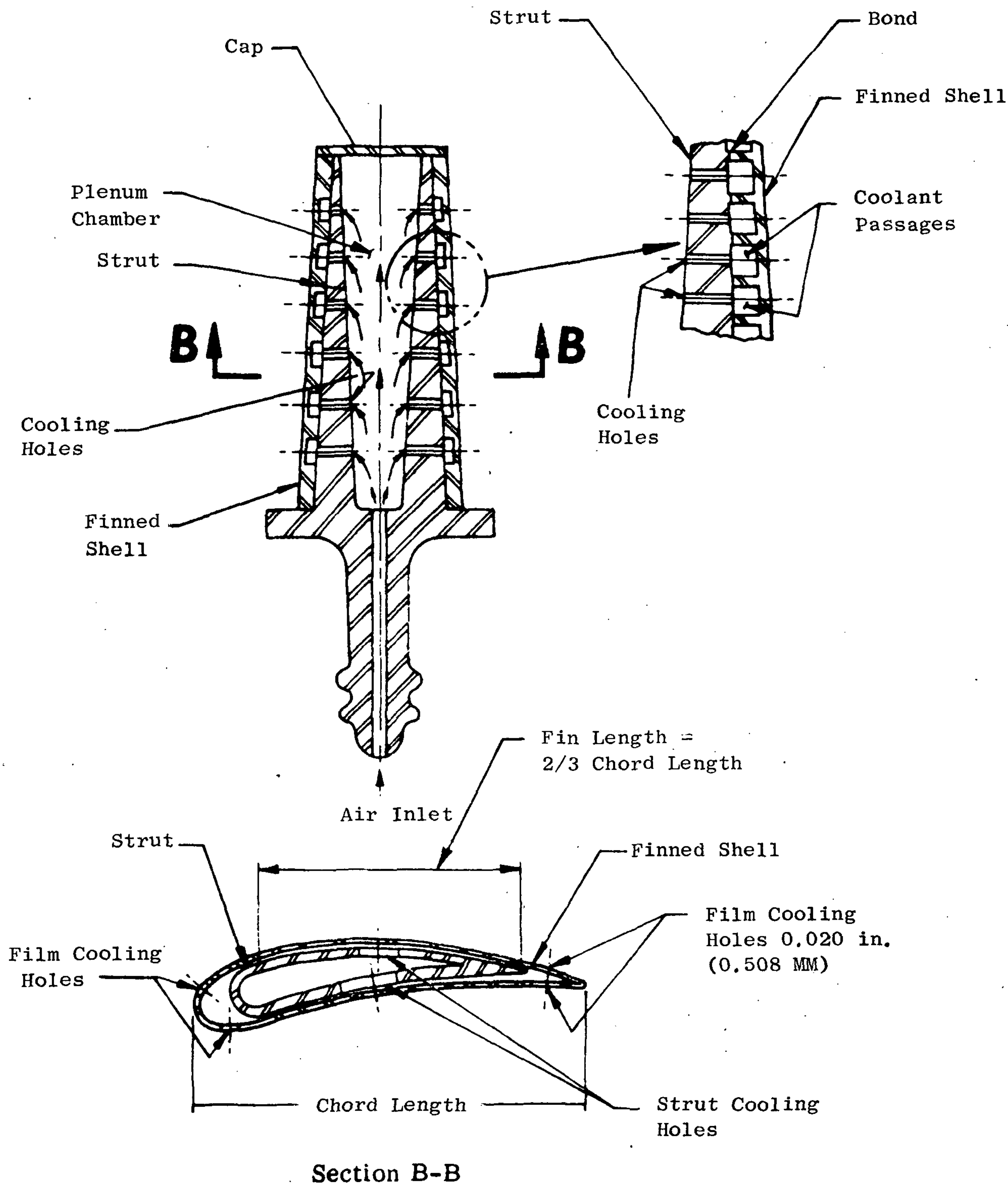


Figure 1. Example of an Advanced Air Cooled Blade Incorporating a Strut with Finned Sheet Joined to the Strut.

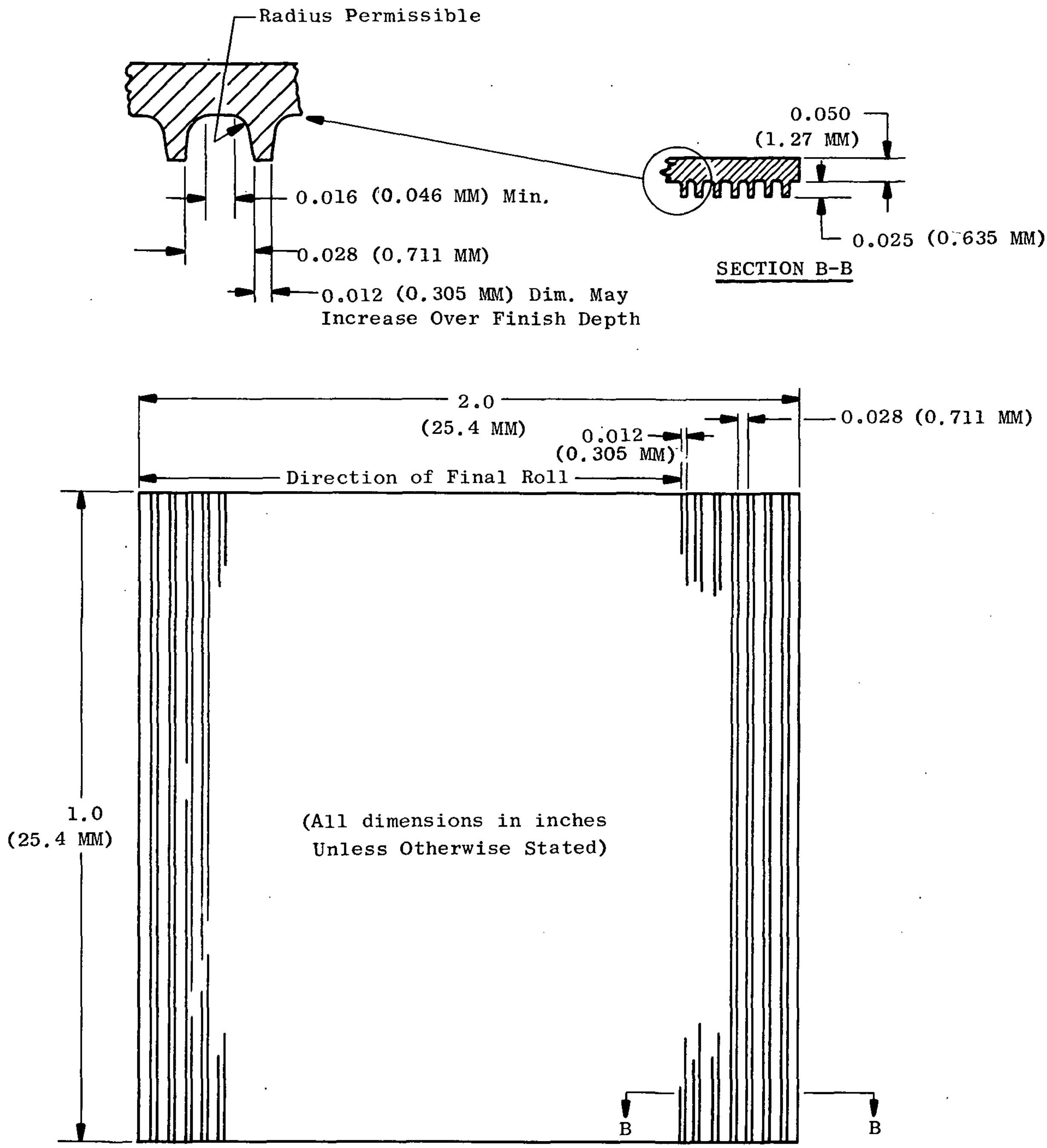
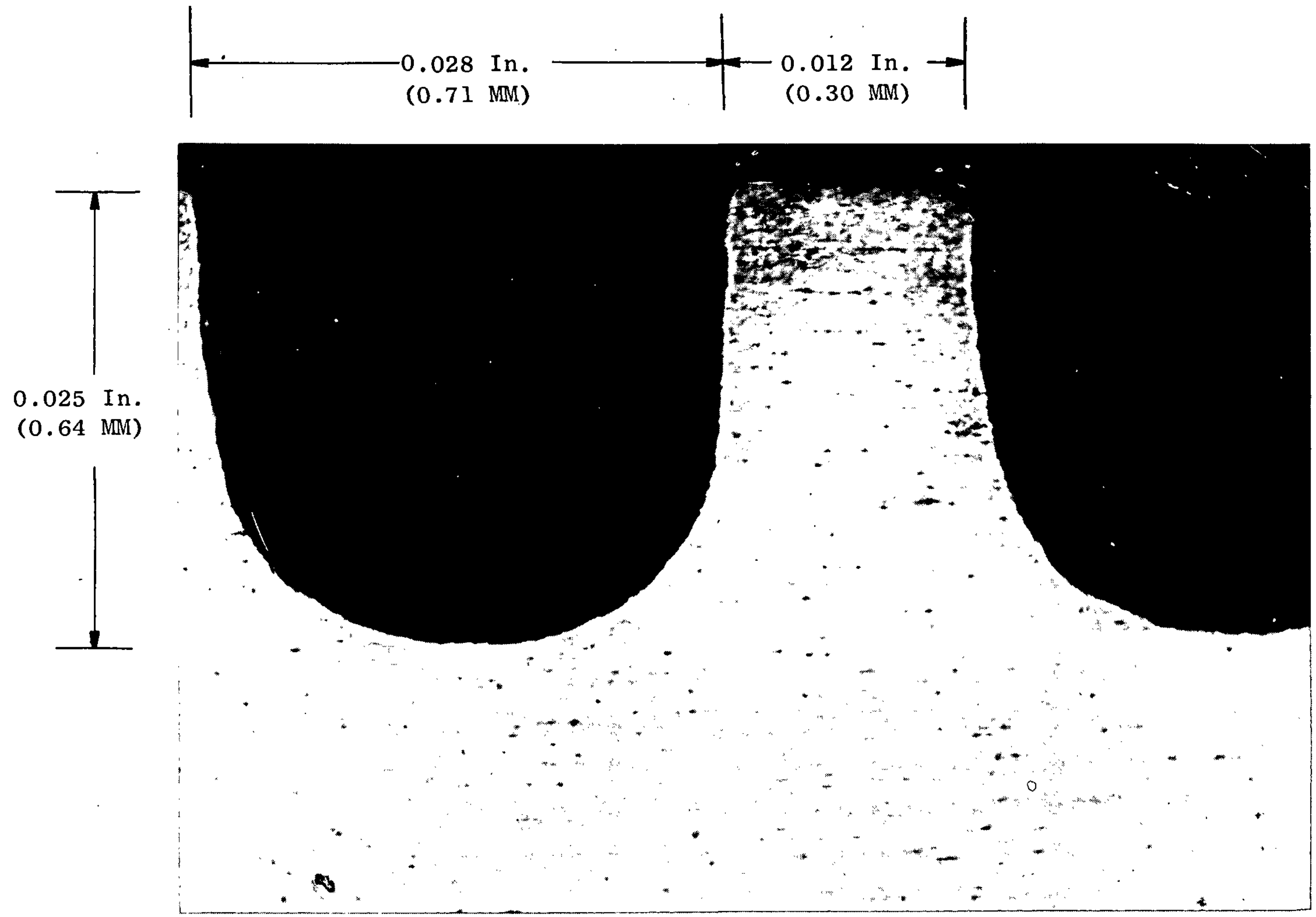
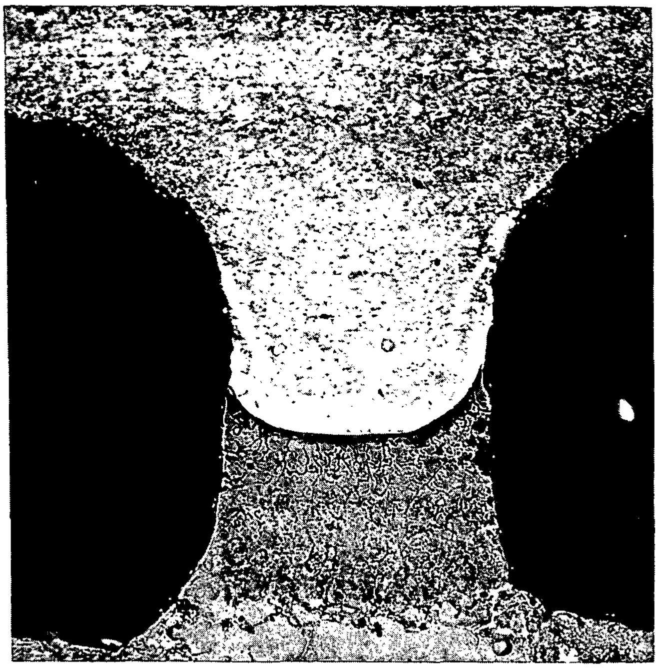


Figure 2. Finned Shell Specimen.



Neg. B6933 100X

Figure 3. Typical Fin Cross Section.

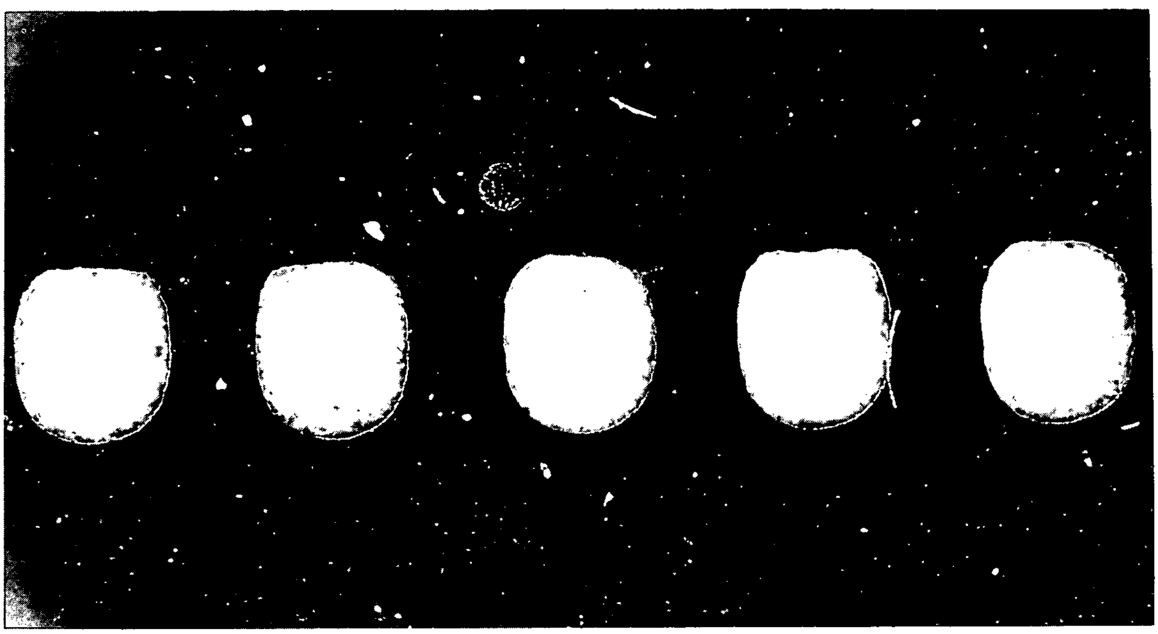


Mount A8812 100X

Mount A13132 100X

Figure 4. TDNiCr Finned Shell, Rene' 80 Joints Made with B-28 (Rene' 80 + 2% B) and B-1 (Rene' 80 + 5% Si).

Neg. C69081105 6X



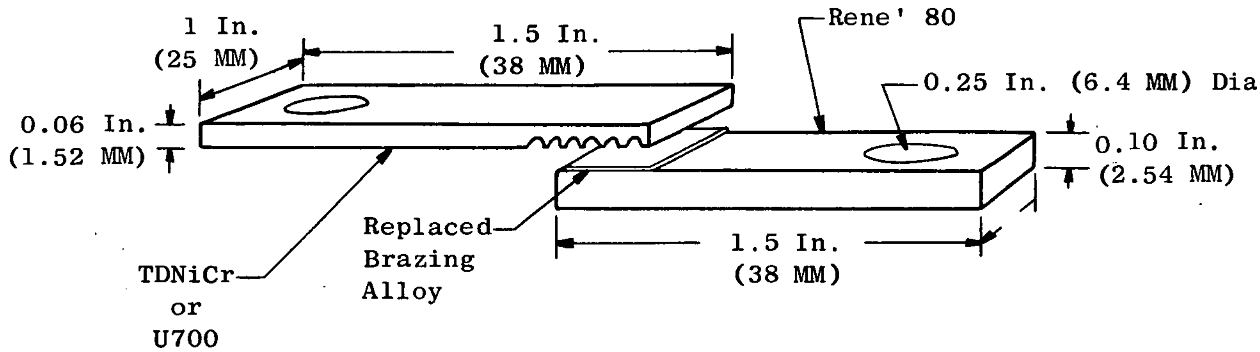
Neg. C69081104 33X

Figure 5. TDNiCr Finned Shell Specimens Activated Diffusion Brazed with B-28 to Rene' 80 Strut Material Showing Joint Soundness and Cavity Configuration.

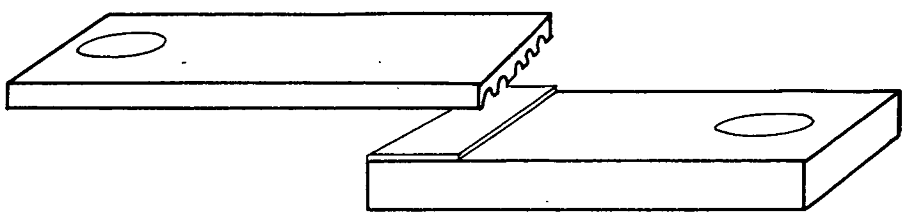
0 PSI (0 kPa) | 15 PSI (103kPa) | 40 PSI (276kPa)

Mount A12363 | Mount A12570 | Mount A12571 | 100X

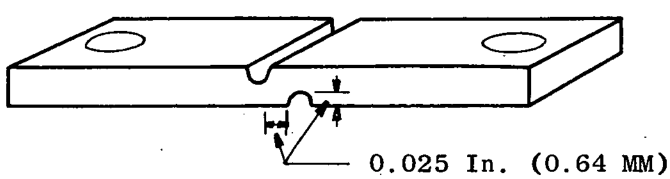
Figure 6. Effect of Brazing Pressure on Joint Quality of TDNiCr Finned Shells Joined to Rene' 80.



Shear Test Specimen-Fins Transverse to Loading Axis



Shear Test Specimen-Fins Parallel to Loading Axis



Parent Metal Shear Test Specimen

Figure 7. Finned Overlap Shear Test Specimens.

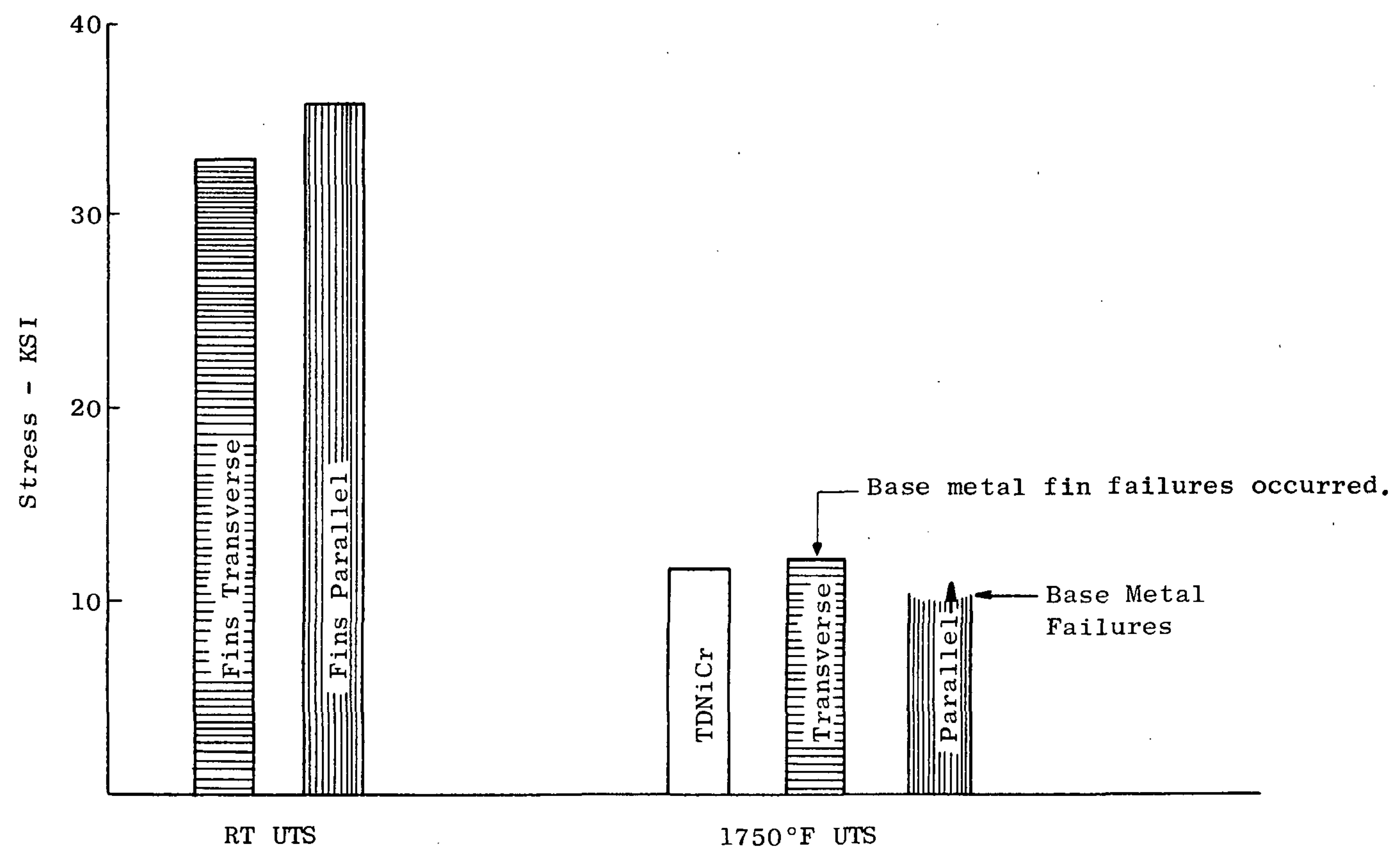


Figure 8. Overlap Shear Tensile Strength of Activated Diffusion Brazed Finned TDNiCr Rene' 80 Using B-1 Brazing Alloy.

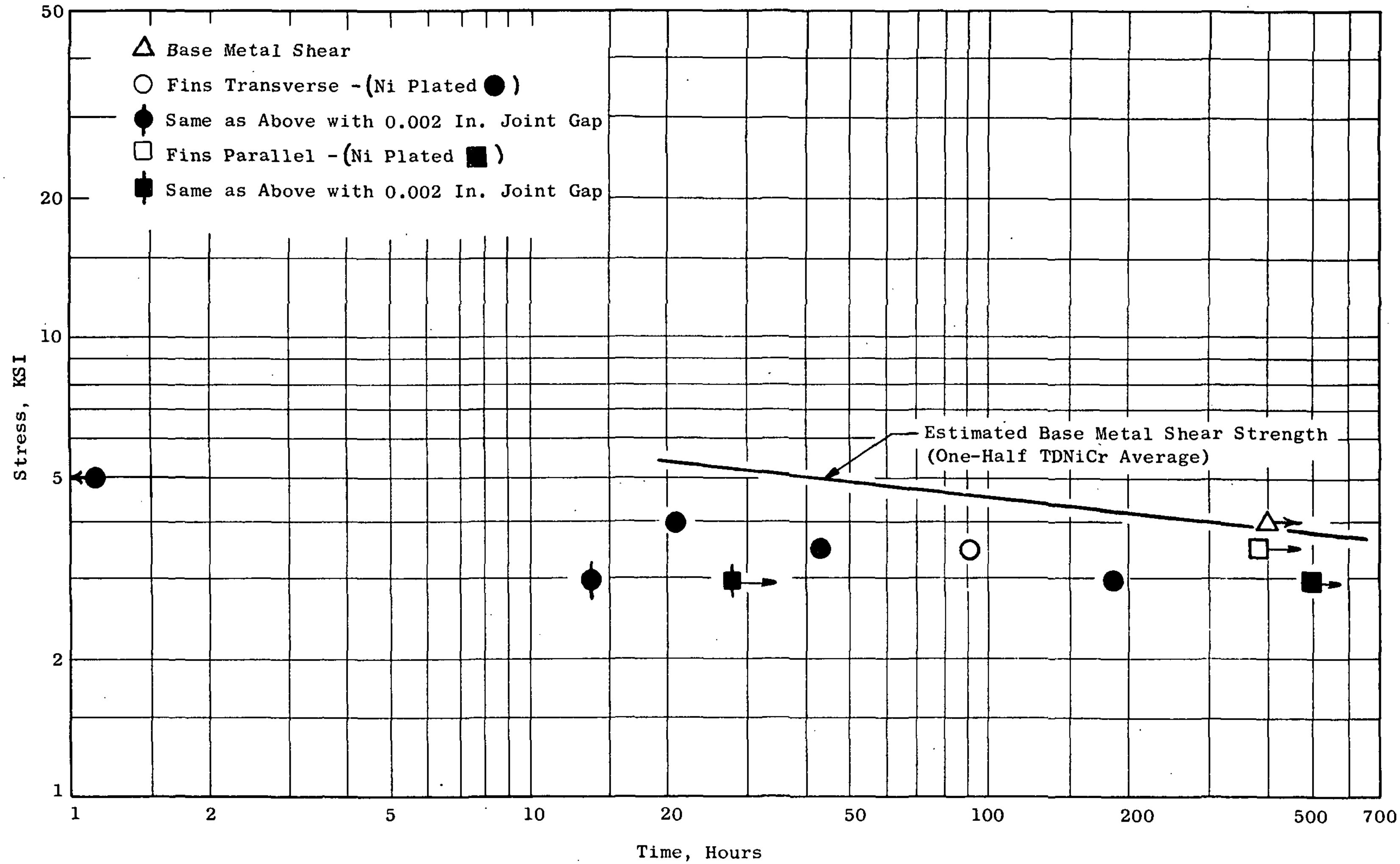
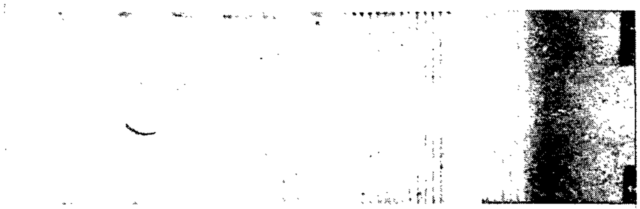


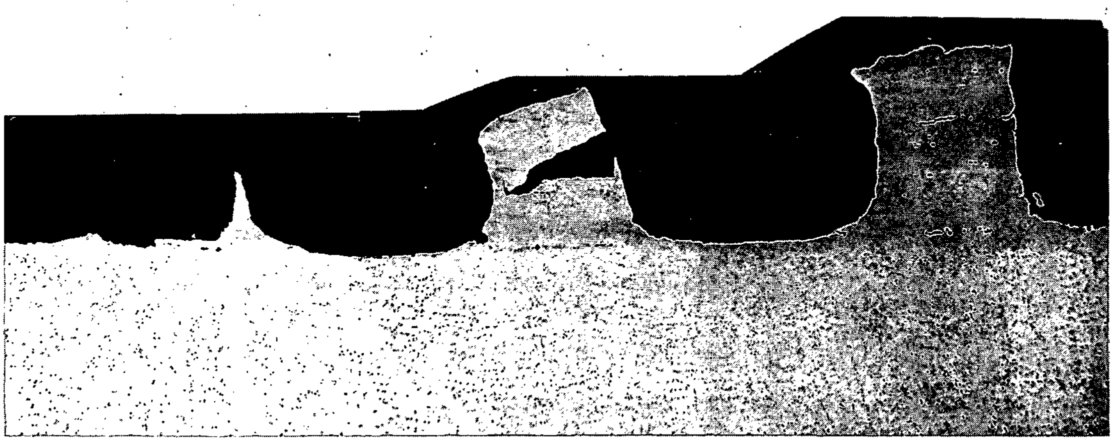
Figure 9. 1750°F (1228 K) Overlap Shear Stress Rupture Strength of Activated Diffusion Brazed Finned TDNiCr, Rene' 80 Using B-1 Brazing Alloy.



a. Typical RT Fracture Appearance (Joint Failure)

b. Typical 1750°F (1228°K Tensile or Stress Rupture Fracture Appearance (Random Joint and Fin Failures)

Neg C70122913



Fractures

TDNiCr

B-1

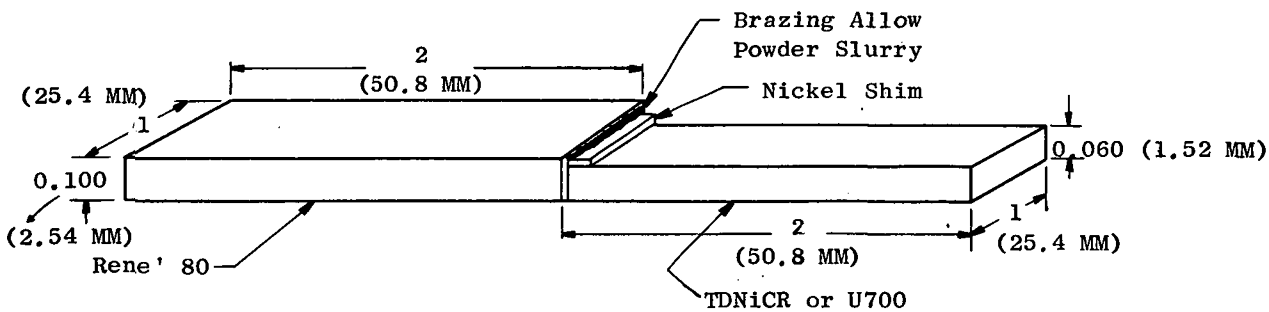
Rene' 80

Neg 9805

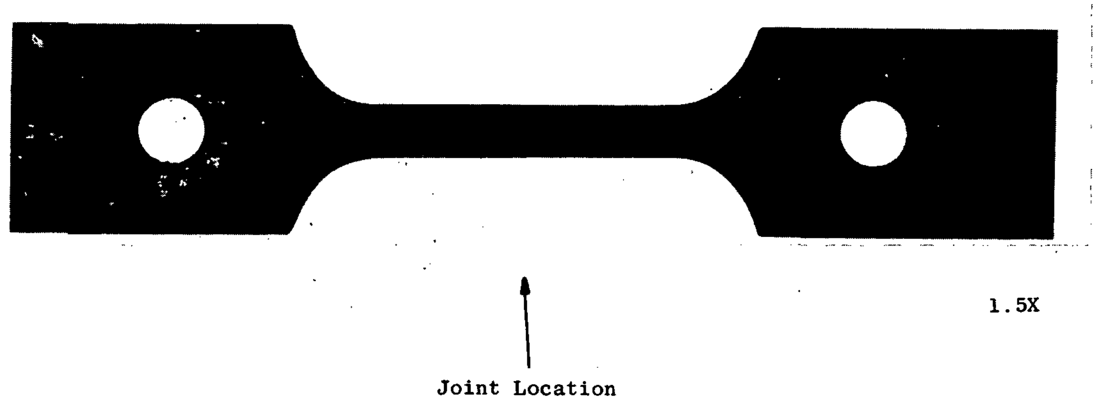
50X

c. Typical 1750°F (1228°K) Tensile of Stress Rupture Cross Section

Figure 10. Typical Fracture Appearance of Finned TDNiCr Activated Diffusion Brazed to Rene' 80.



Specimen Assembly
(All Dimensions in Inches Unless Otherwise Stated)



Test Specimen Configuration

Figure 11. Butt Joint Specimen.

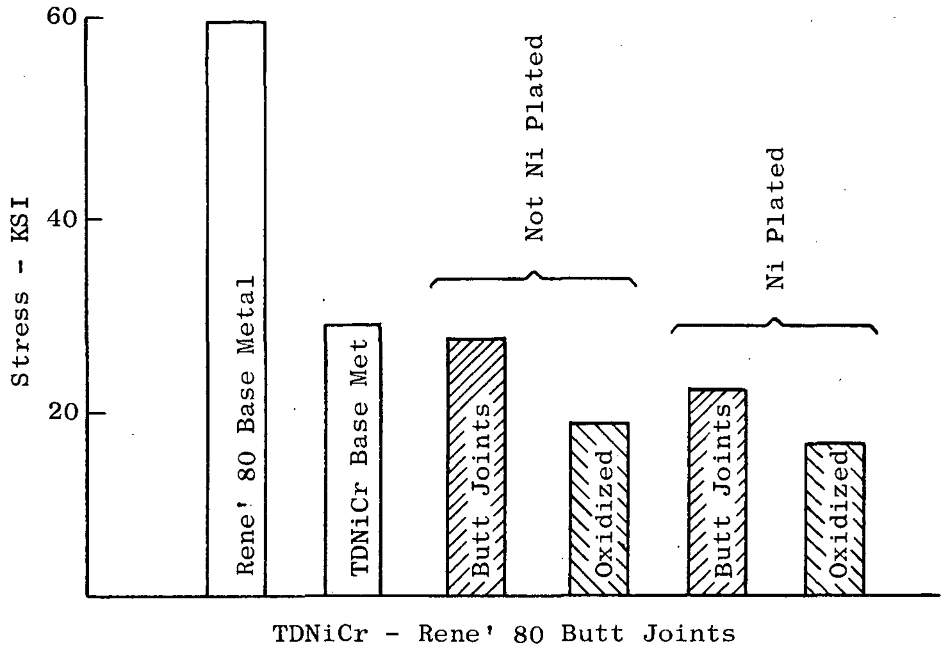


Figure 12. 1750°F (1228°K) Ultimate Strength of Activated Diffusion Brazed Butt Joints of TDNiCr to Rene' 80 Using B-1 Brazing Alloy.

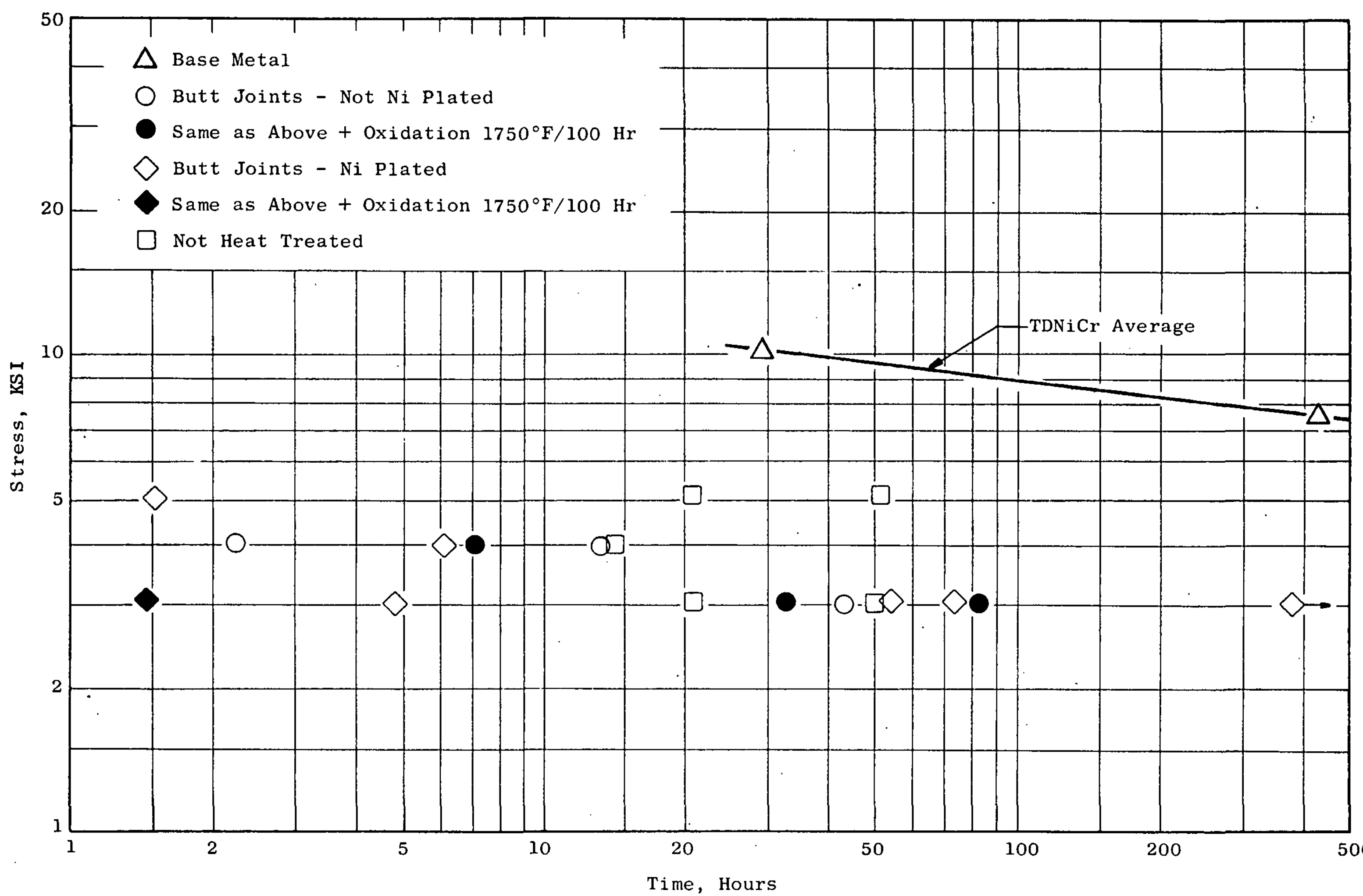
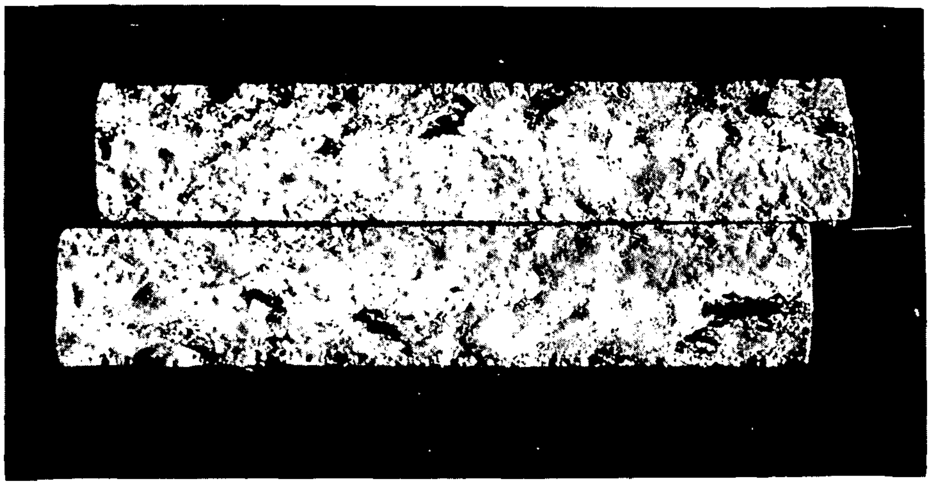


Figure 13. 1750°F (1228 K) Butt Joint Stress Rupture Properties of TDNiCr Activated Diffusion Brazed to Rene' 80 Using B-1 Brazing Alloy.



Neg. C69100234 20X

Specimen History:

Brazing Alloy	B-1
Brazing Temperature - Time	2225°F (1491°K)/30 Min
Post Brazing Heat Treatment	2000°F (1366°K)/4 Hr 1925°F (1325°K)/4 Hr 1550°F (1089°K)/16 Hr
1750°F (1228°K) Ultimate Tensile Strength	19.4 KSI (134 MPa)
Ductility	0.4% Elongation

Figure 14. Typical Fracture Appearance of TDNiCr to Rene' 80 Butt Joint Specimen After 1750°F (1228°K) Tensile Testing.

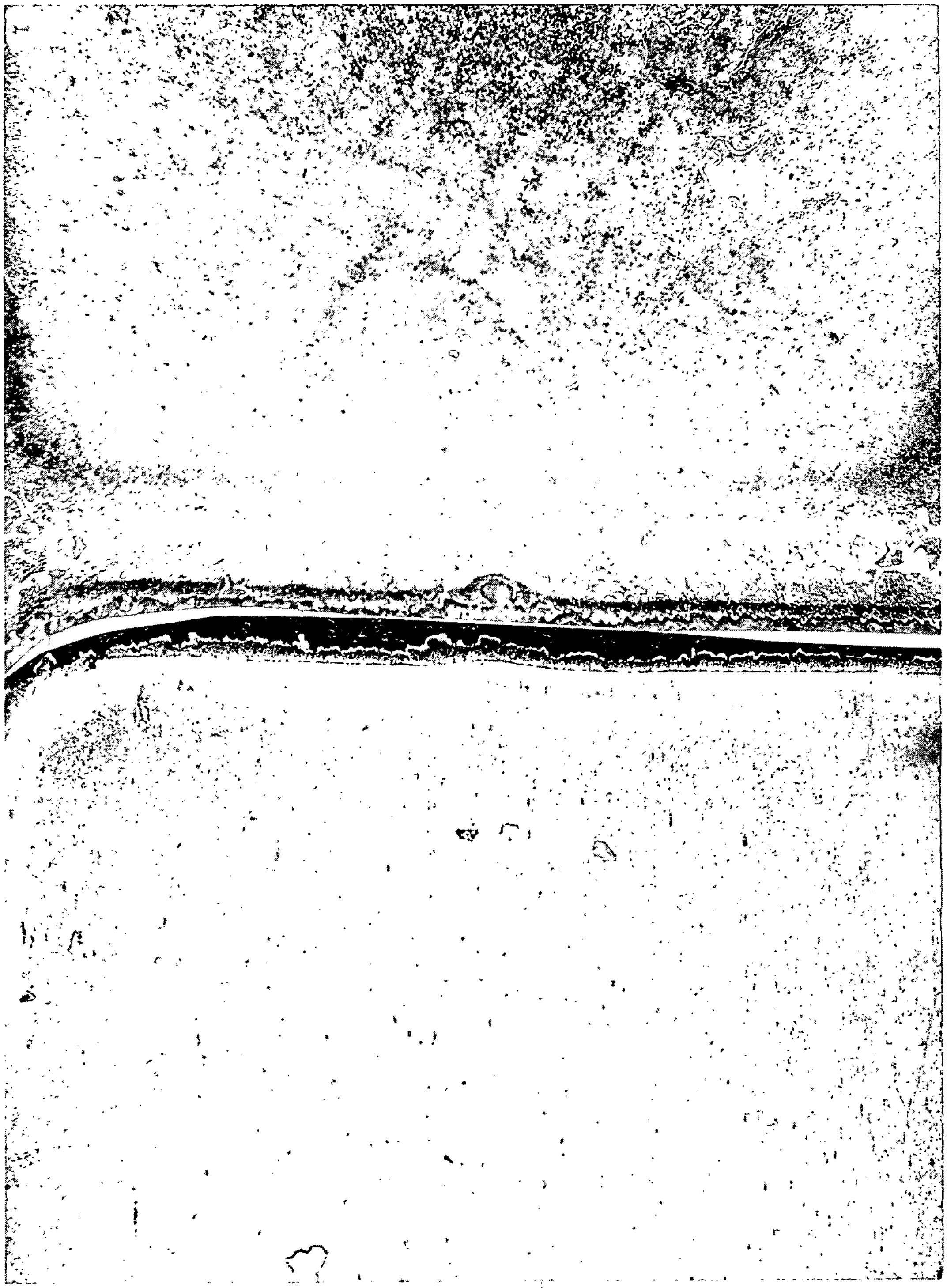
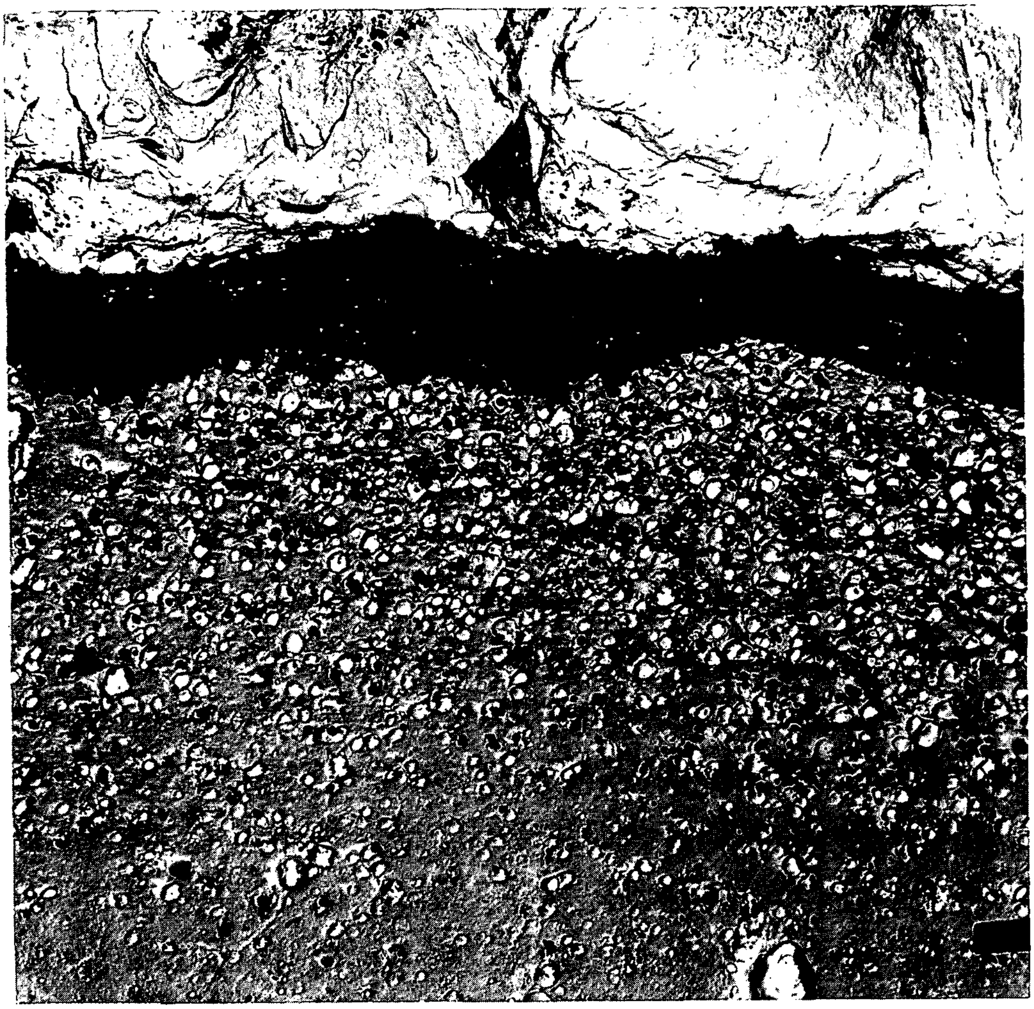
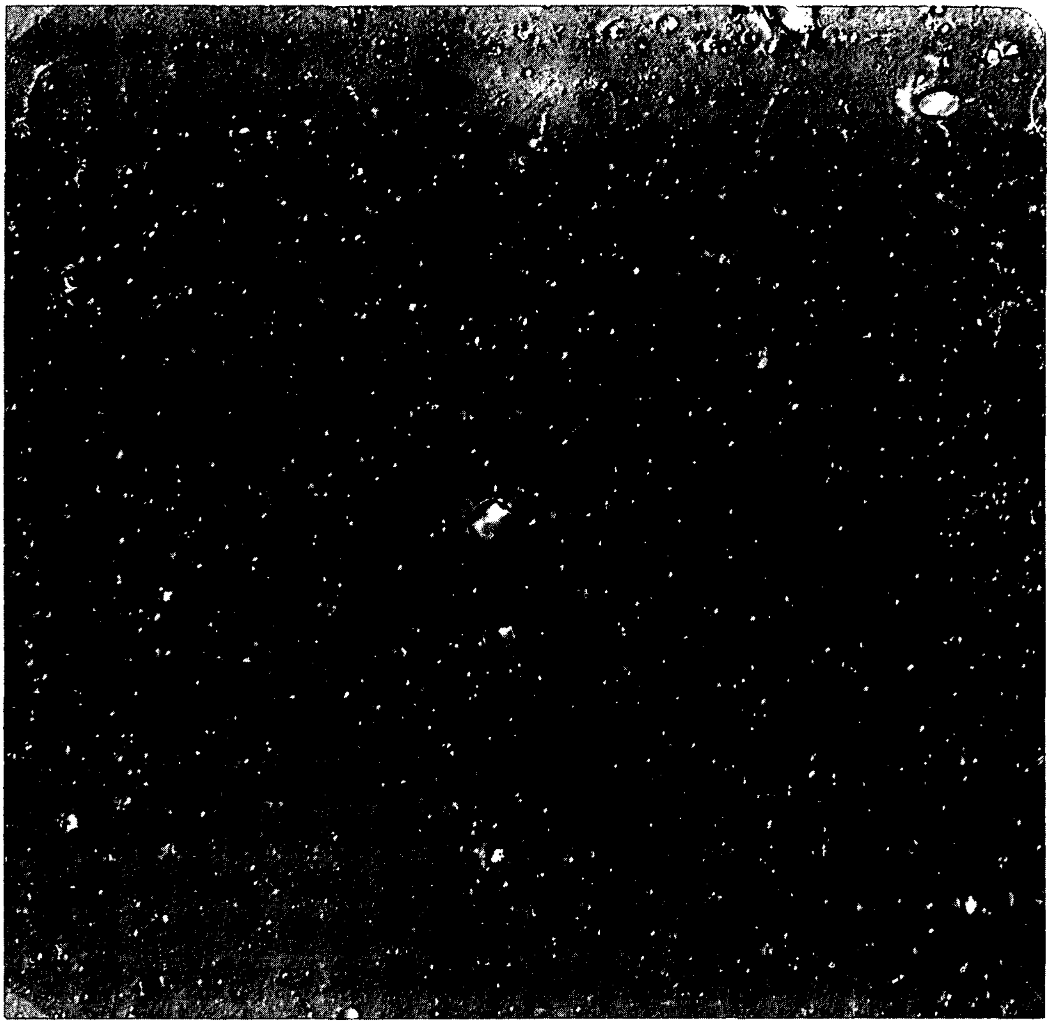


Figure 15. Cross Section of Fractured Bar of Figure 14 Showing Fracture Traversing Through TDNiCr Immediately Adjacent to the Solid-Liquid Interface.



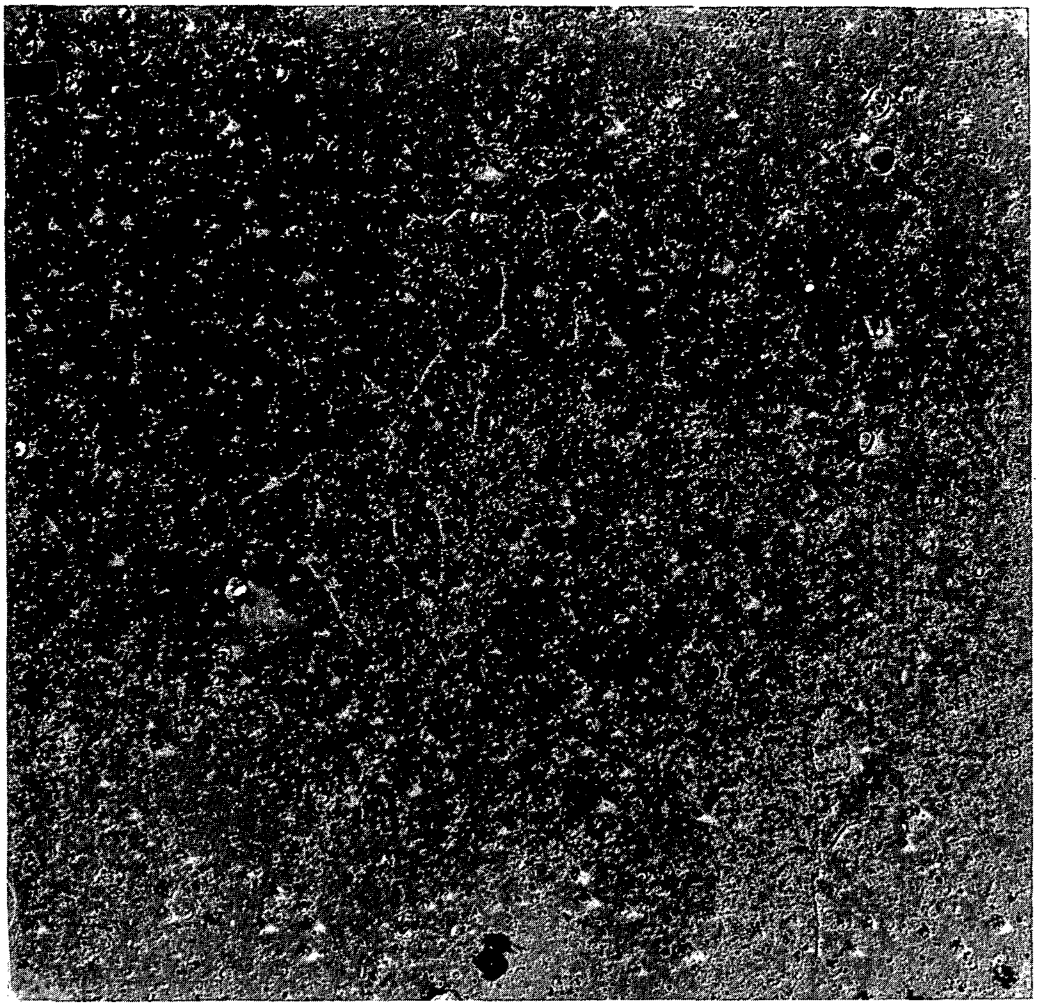
Neg. 562-1 6000X

Figure 16. Electron Micrograph of TDNiCr Side of Fracture Showing Agglomerated Thoria Immediately Adjacent to Fracture Edge.



Neg. 562-2 6000X

Figure 17. Electron Micrograph of TDNiCr Side of Fracture, 0.001 Inch (0.025 MM) from the Fracture Edge, Showing a Portion of the Thoria-Depleted Band.



Neg. 562-3 6000X

Figure 18. Electron Micrograph in TDNiCr, 0.005 Inch (0.13 MM) from the Fracture, Showing Normal Thoria Dispersion.

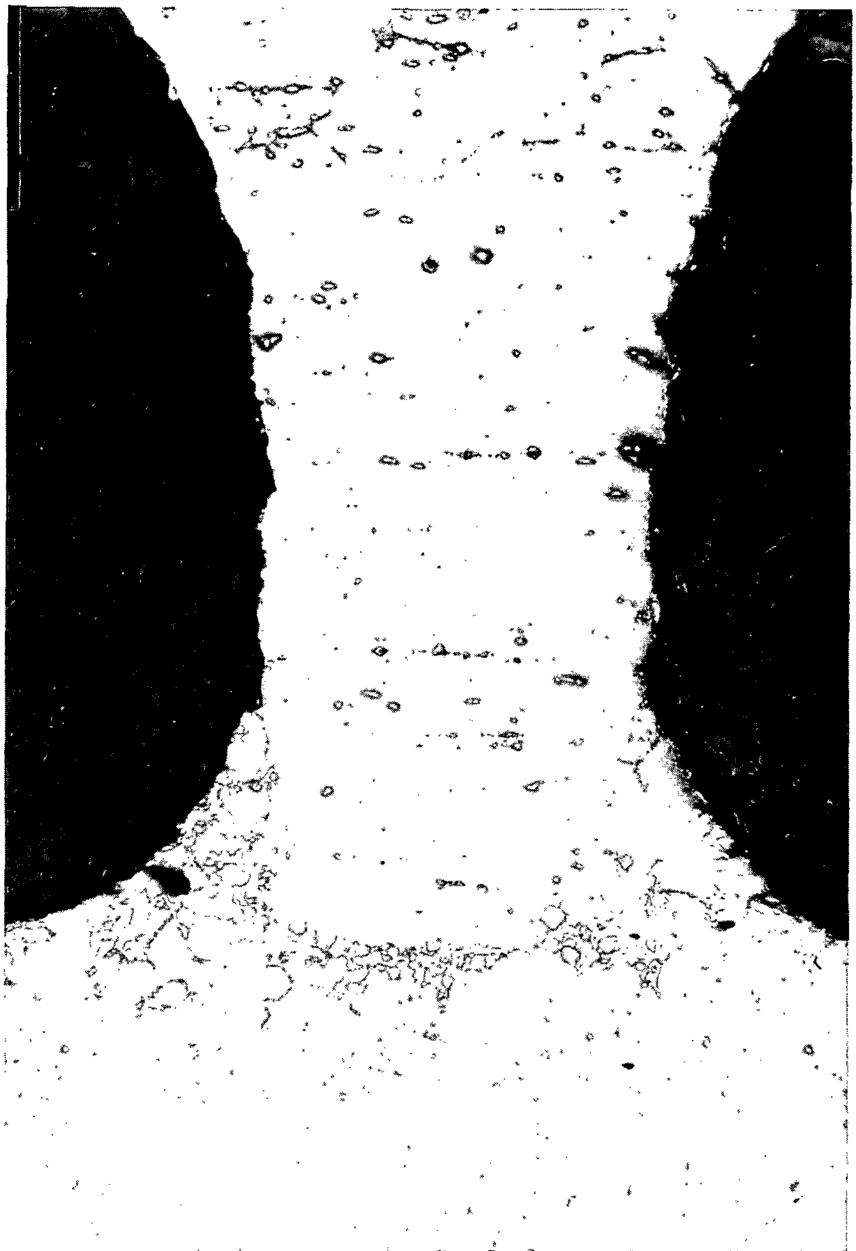


Figure 19. Typical Microstructure of Activated Diffusion Brazed U700 to Rene' 80 Using B-1 Brazing Alloy.

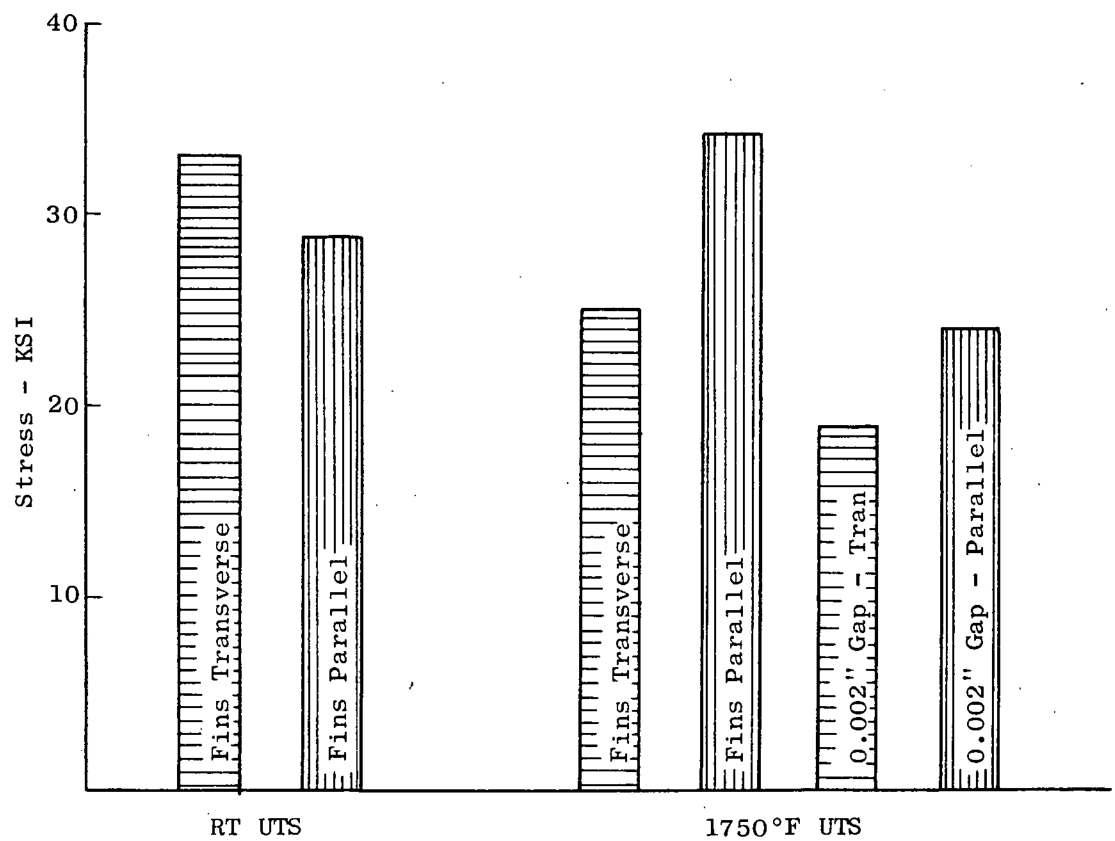


Figure 20. Shear Tensile Strength of Finned U700 Activated Diffusion Brazed to Rene' 80 Using B-1 Brazing Alloy.

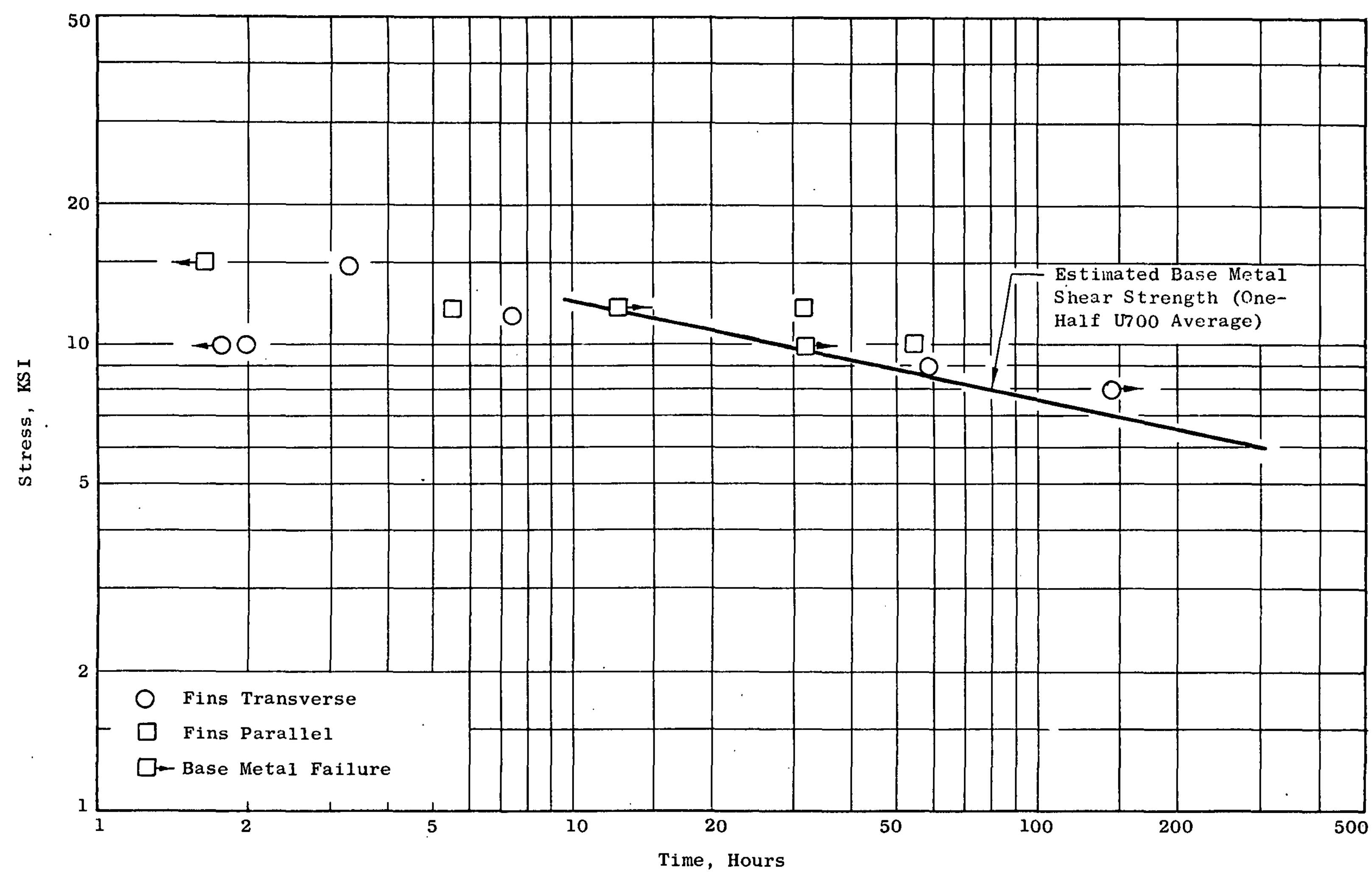


Figure 21. 1750°F (1228 K) Shear Stress Rupture Strength at Finned U700 Activated Diffusion Brazed to Rene' 80 Using B-1 Brazing Alloy.

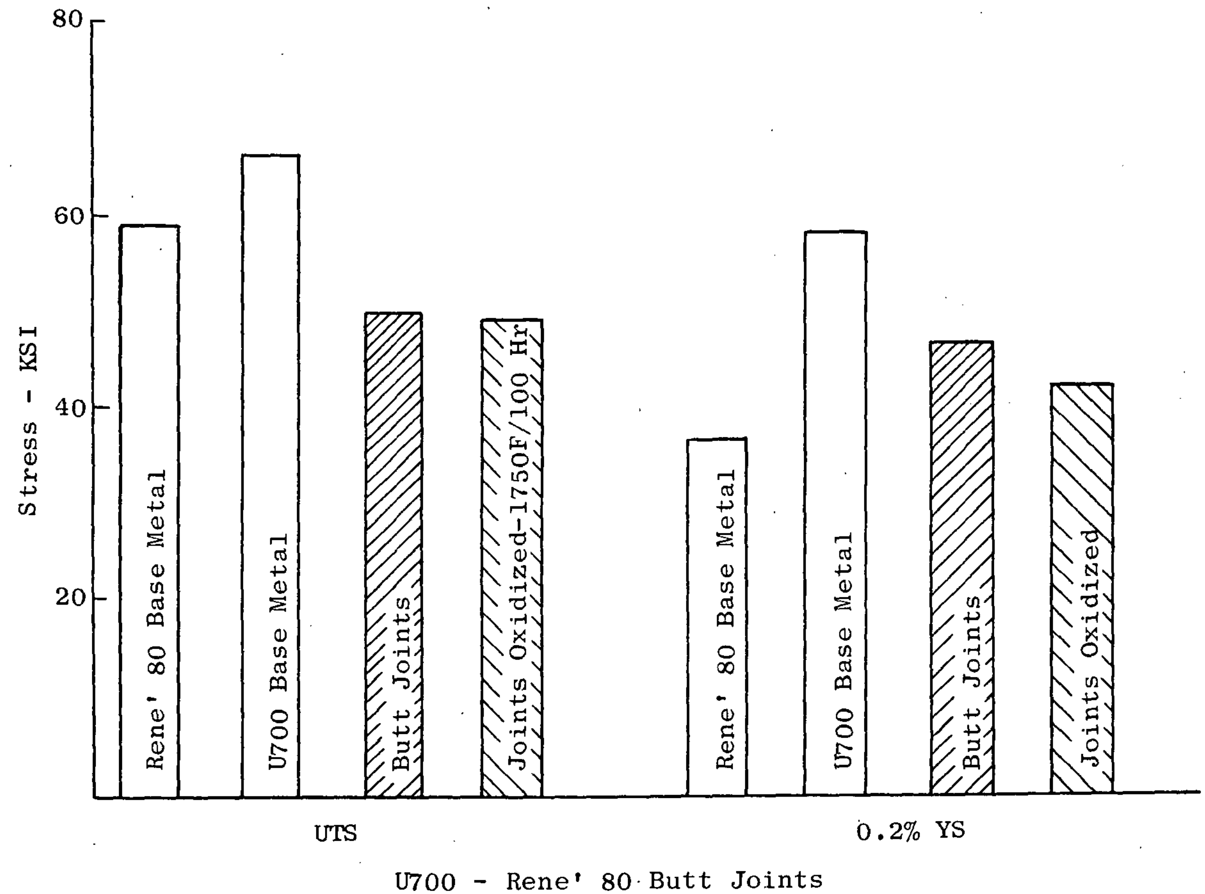


Figure 22. 1750°F (1228 K) Ultimate Tensile Strength of Activated Diffusion Brazed Butt Joints of U700-Rene' 80 Using B-1 Brazing Alloy.

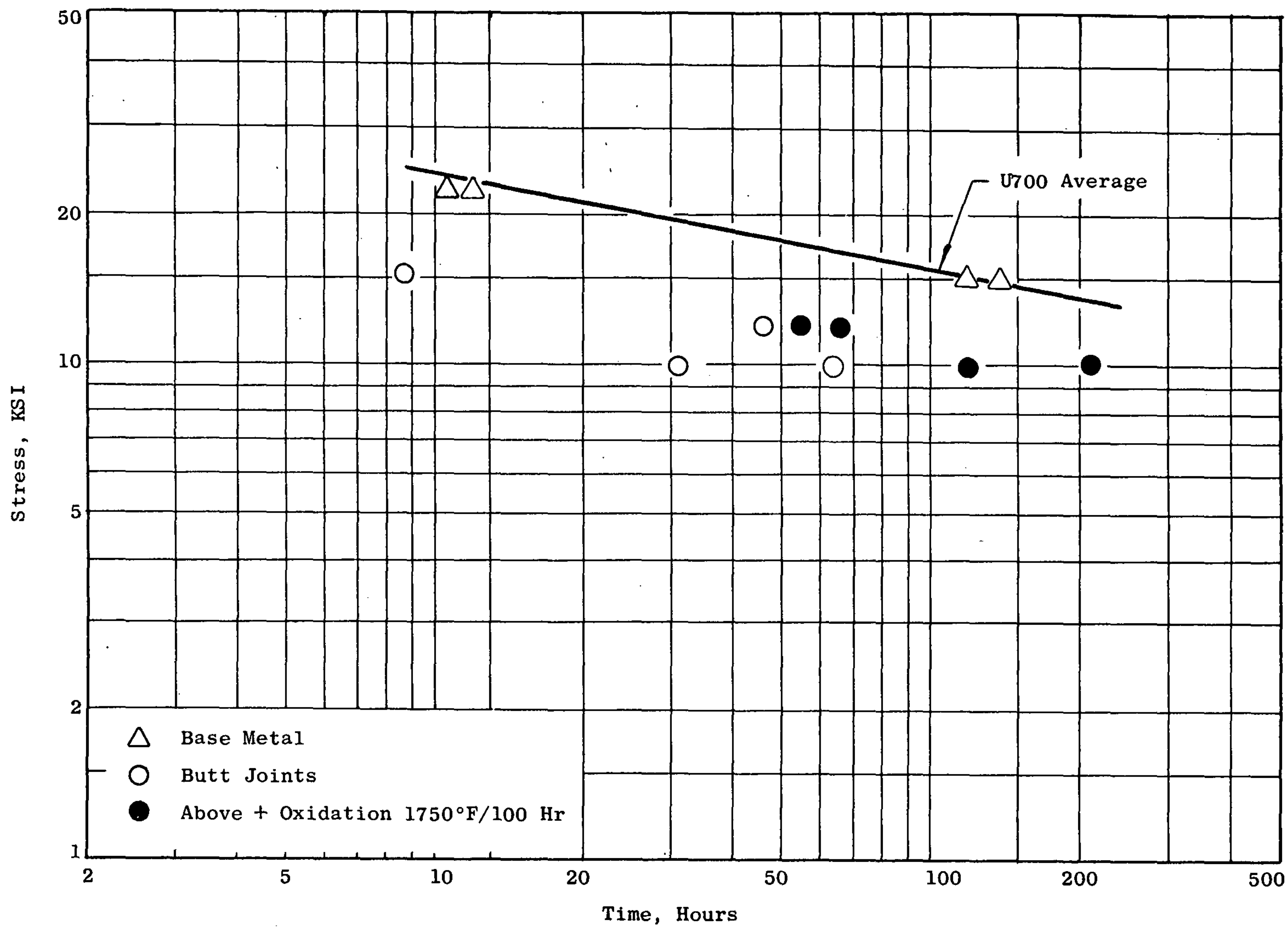


Figure 23. 1750°F (1228 K) Butt Joint Stress Rupture Properties of Finned U700 Activated Diffusion Brazed to Rene' 80 Using B-1 Brazing Alloy.

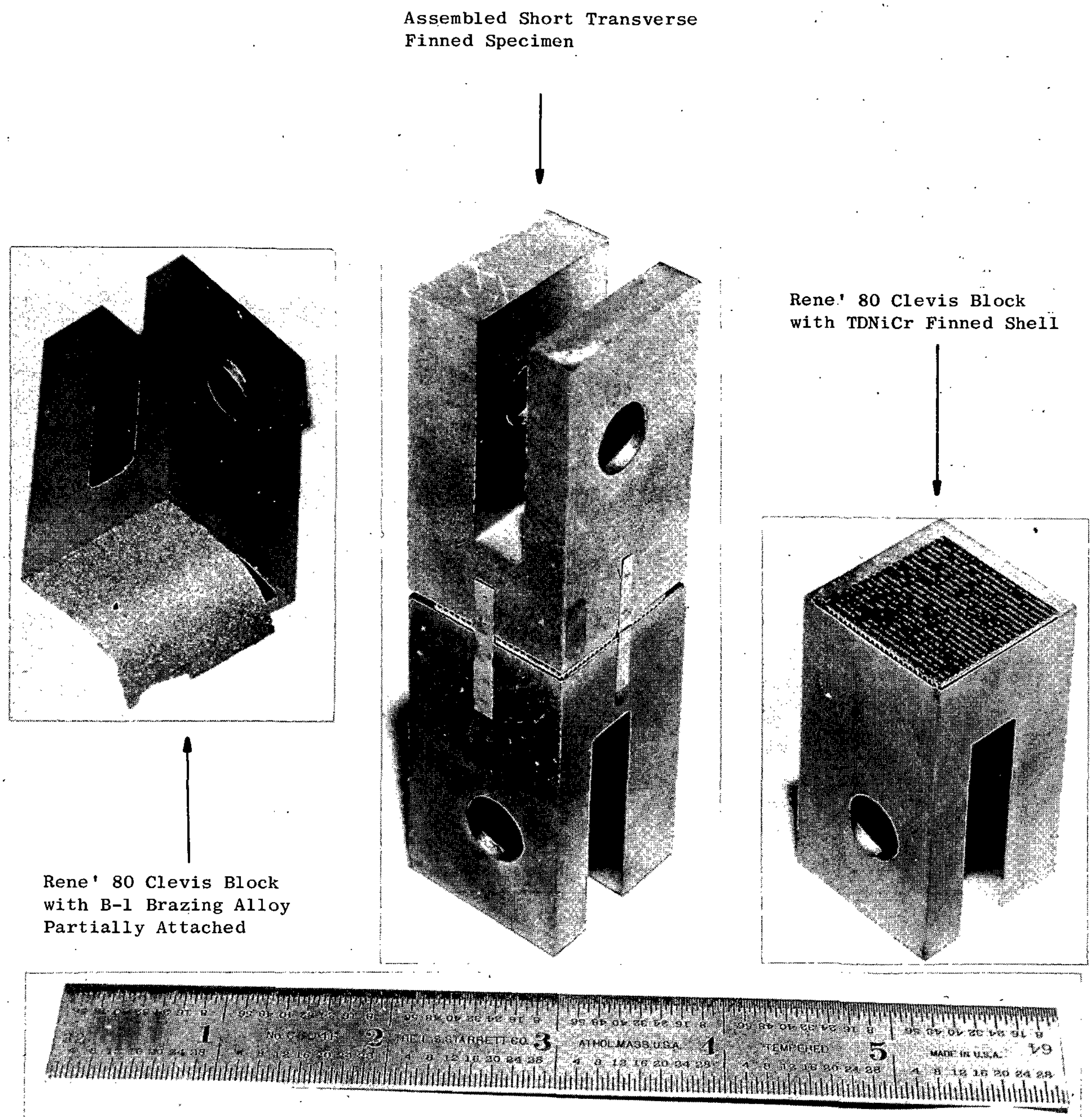


Figure 24. Finned Shell - Rene' 80 Block, Short Transverse Finned Butt Joint Specimen.

Z	
Finned Shell Dimensions	
TDNiCr	1 x 1 x 0.060 In. (25 x 25 x 1.52 mm)
U700	0.8 x 0.8 x 0.060 In. (20 x 20 x 1.52 mm)

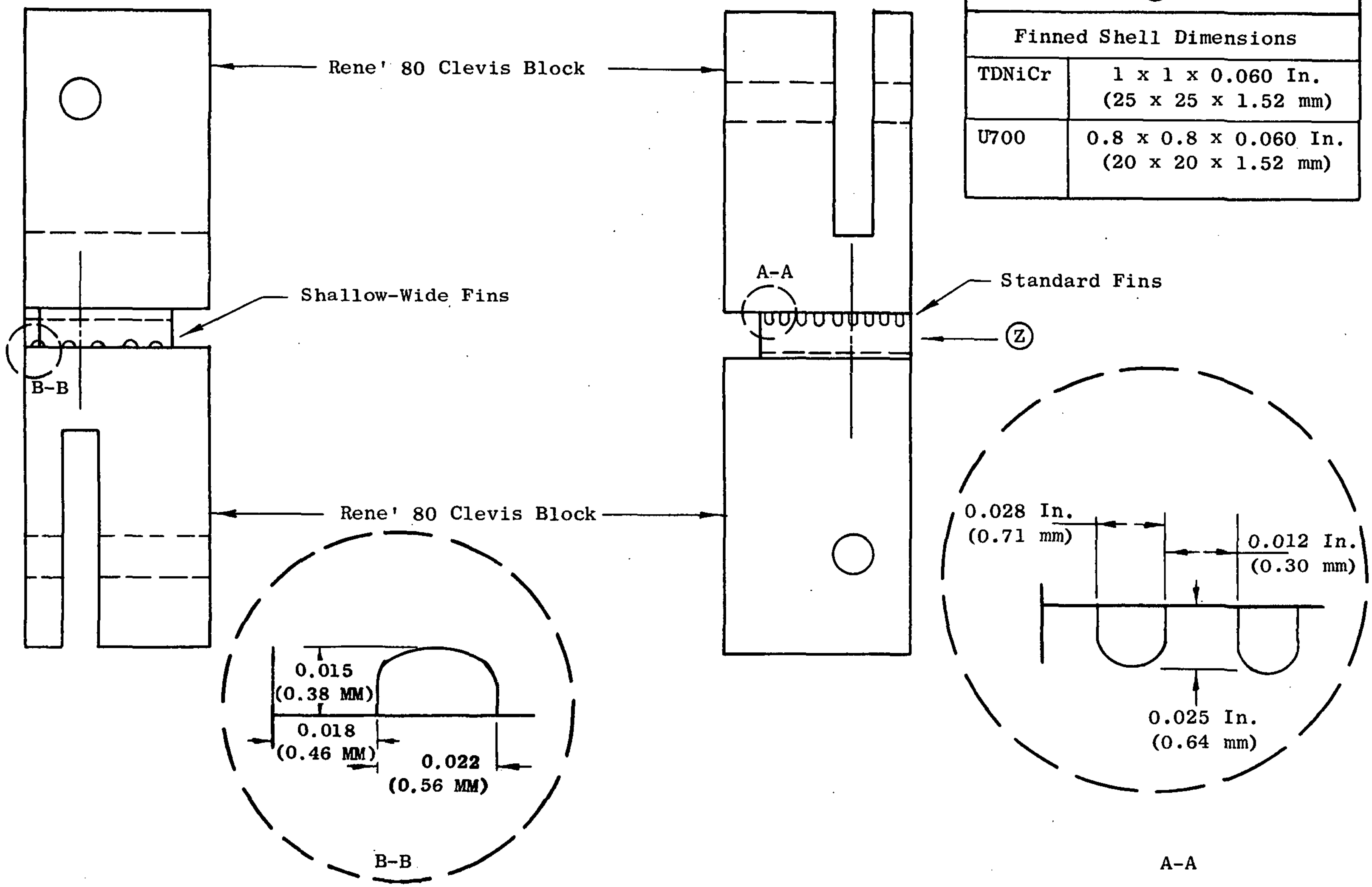


Figure 25. Finned Shell - Rene' 80 Block, Short Transverse Finned Specimen Design.

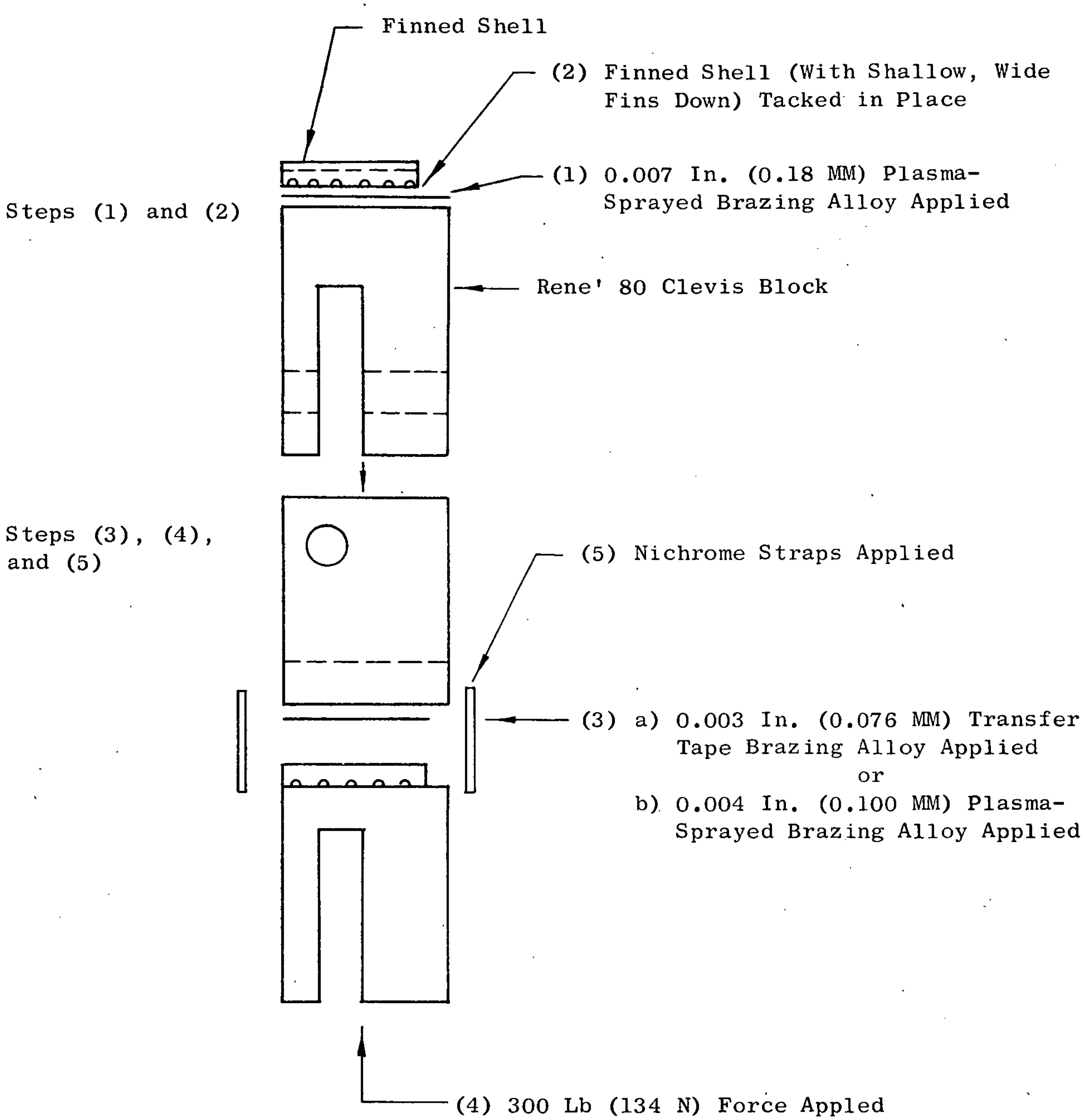


Figure 26. Techniques Used to Assemble a Short Transverse Finned Specimen.

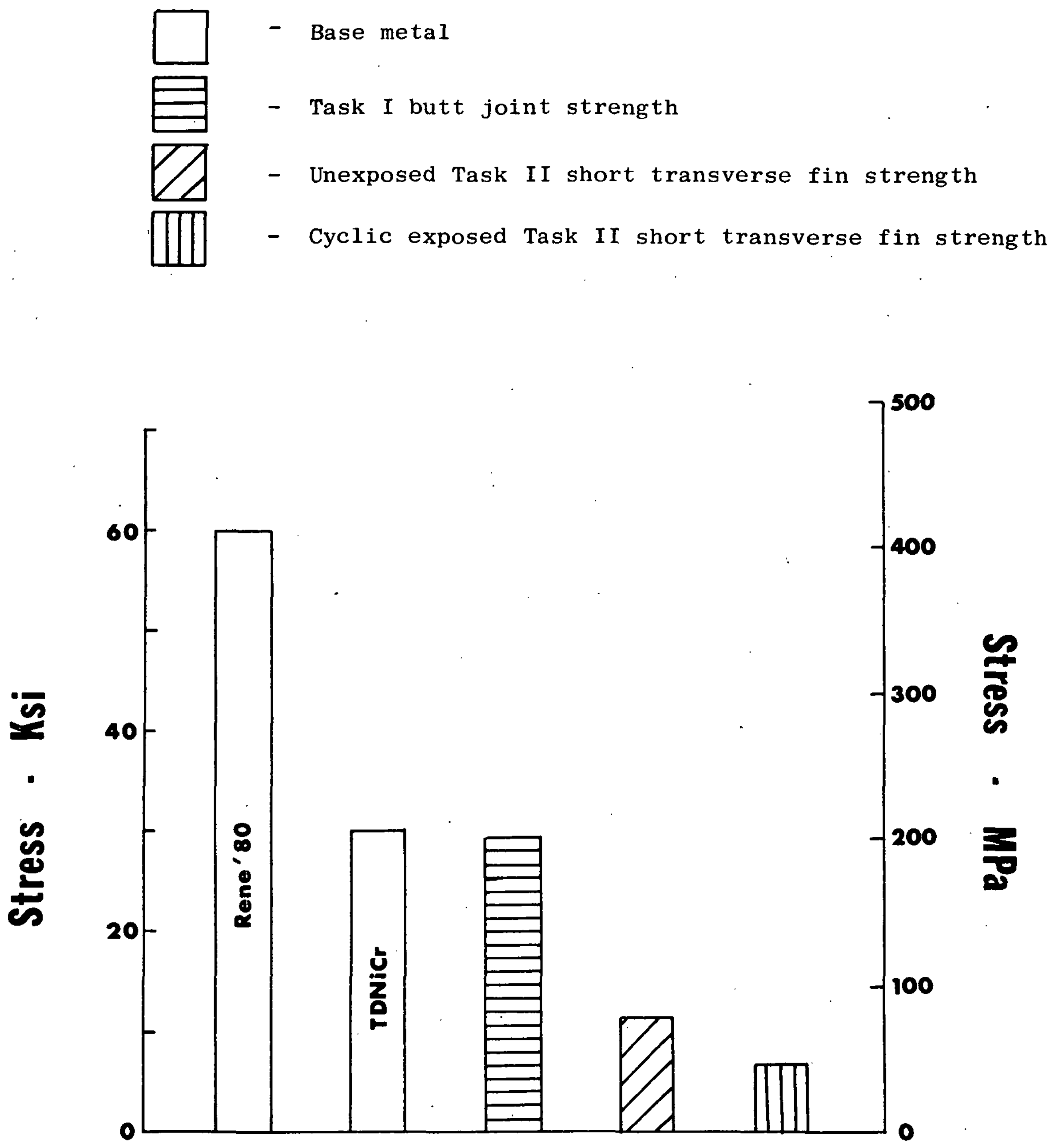


Figure 27. 1750°F (1228 K) Tensile Strength of TDNiCr - Rene' 80 Short Transverse Finned Specimens.

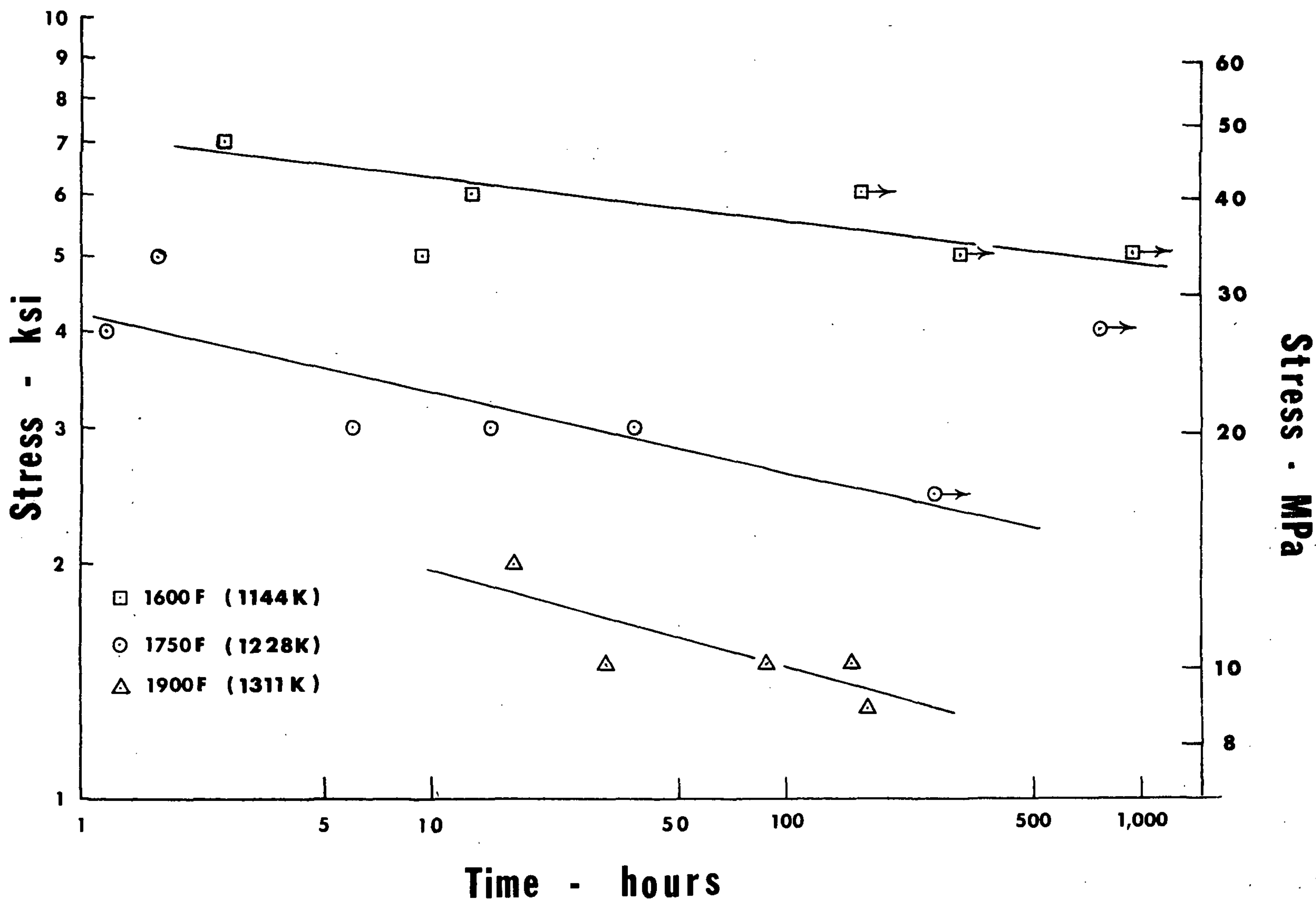


Figure 28. Stress Rupture Life of TDNiCr - Rene' 80 Short Transverse Finned Specimens.

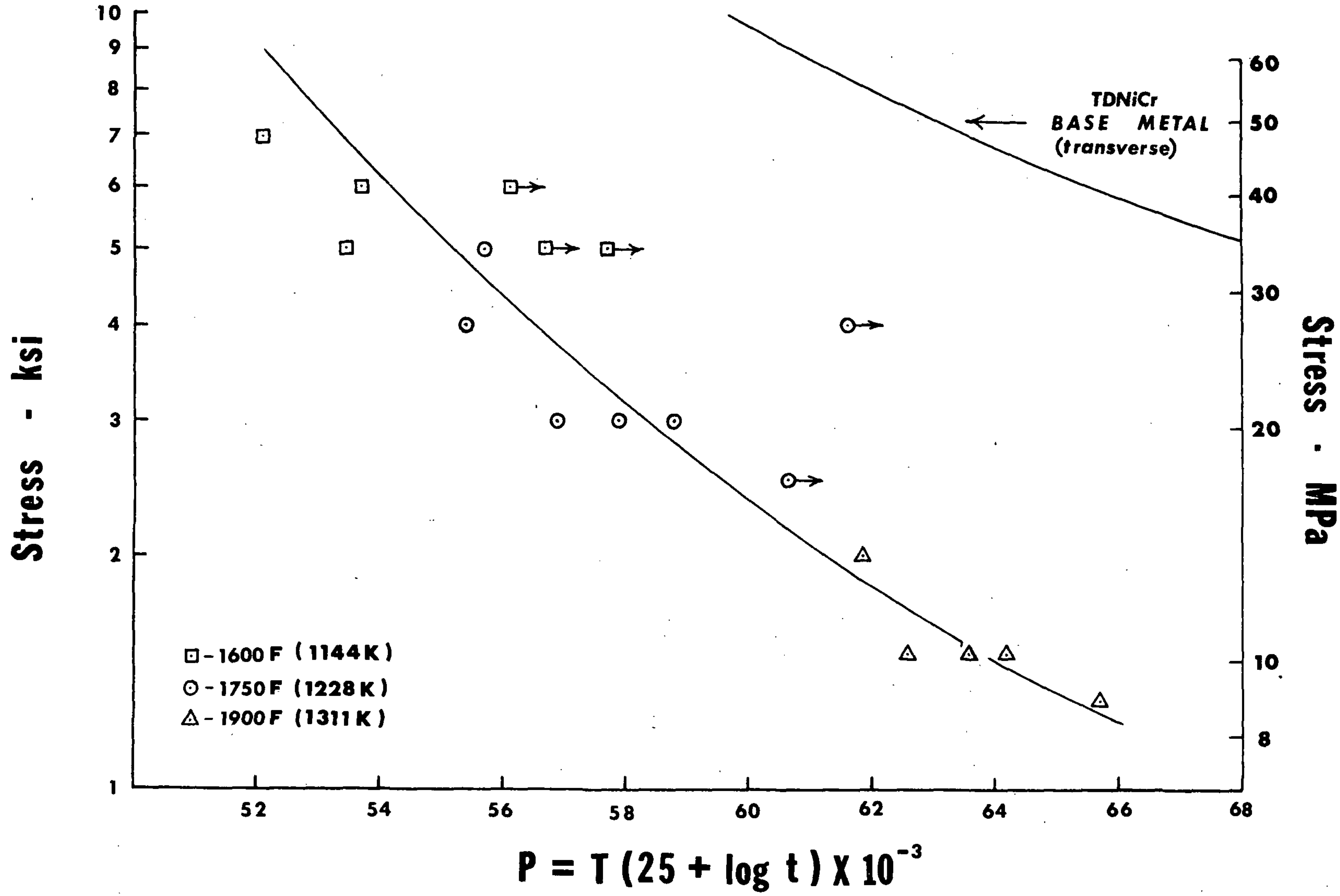


Figure 29. Stress Rupture Strength Versus Larson-Miller Parameter of TDNiCr - Rene' 80 Short Transverse Finned Specimens.

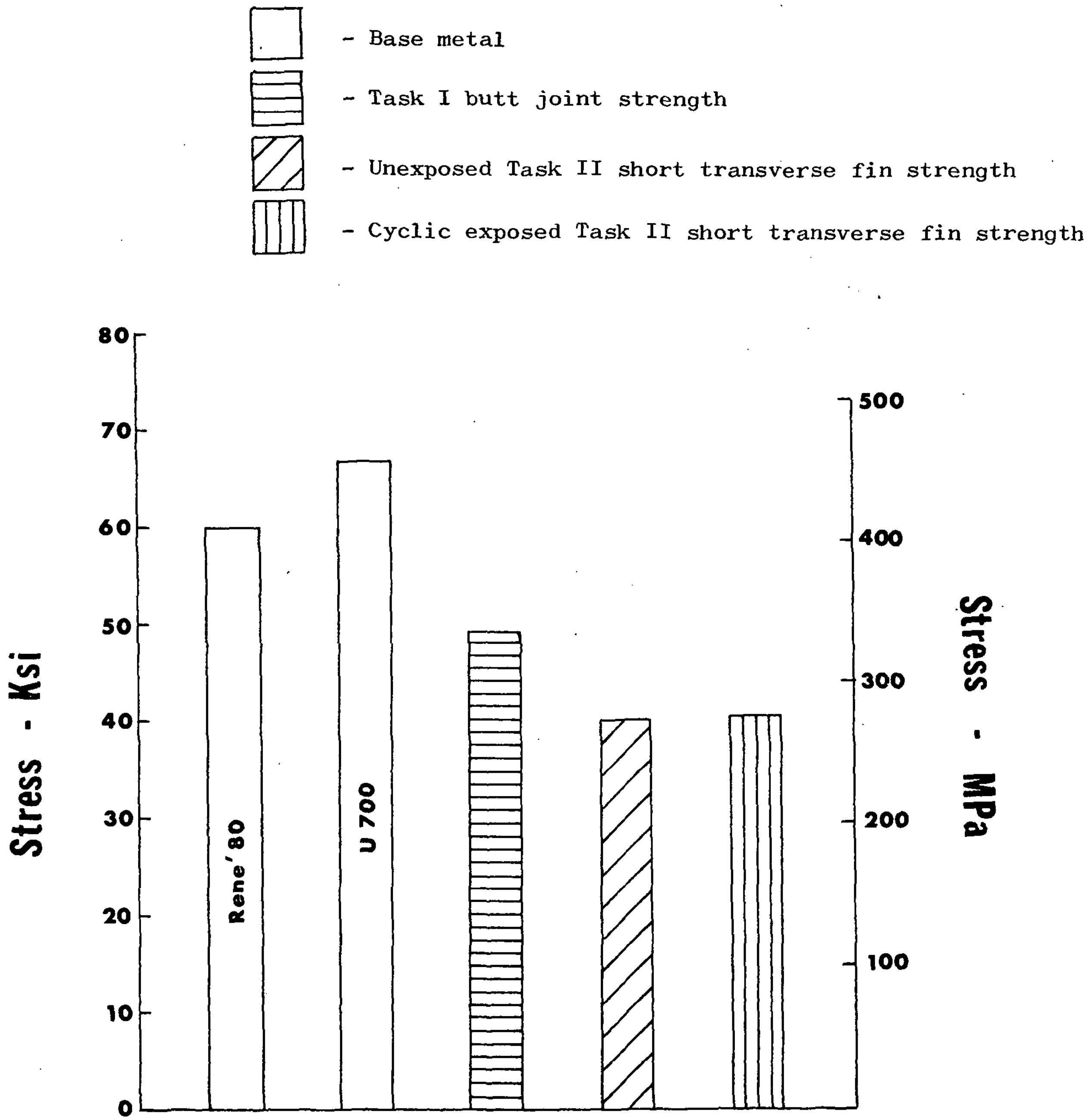
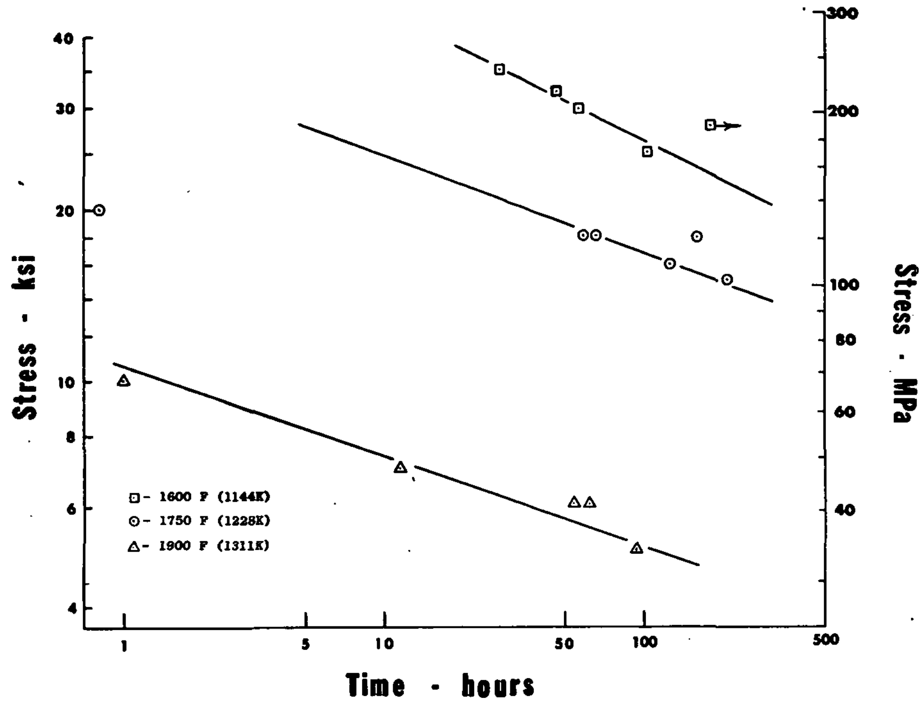
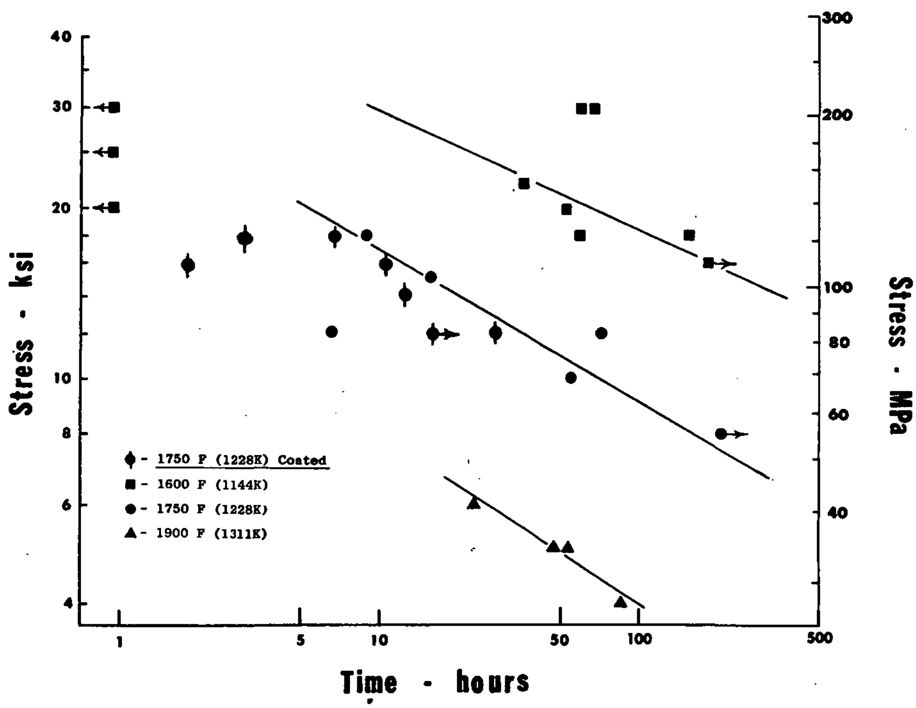


Figure 30. 1750°F (1228 K) Tensile Strength of U700 - Rene' 80 Short Transverse Finned Specimens.



a. Stress rupture life of unexposed U700 - Rene' 80 short transverse finned specimens.



b. Stress rupture life of cyclic exposed U700 - Rene' 80 short transverse finned specimens.

Figure 31. Stress Rupture Life of U700 - Rene' 80 Short Transverse Finned Specimens.

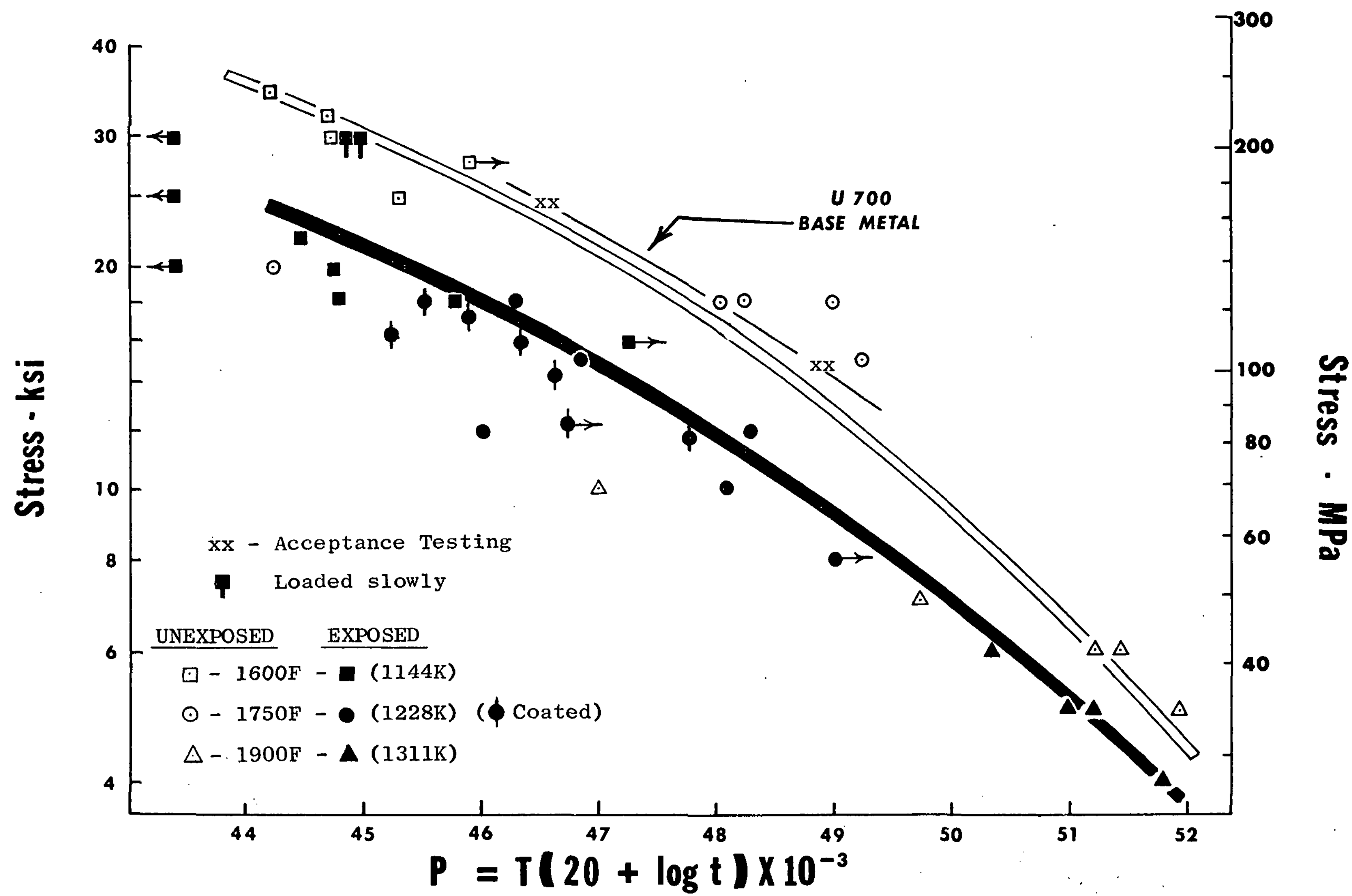
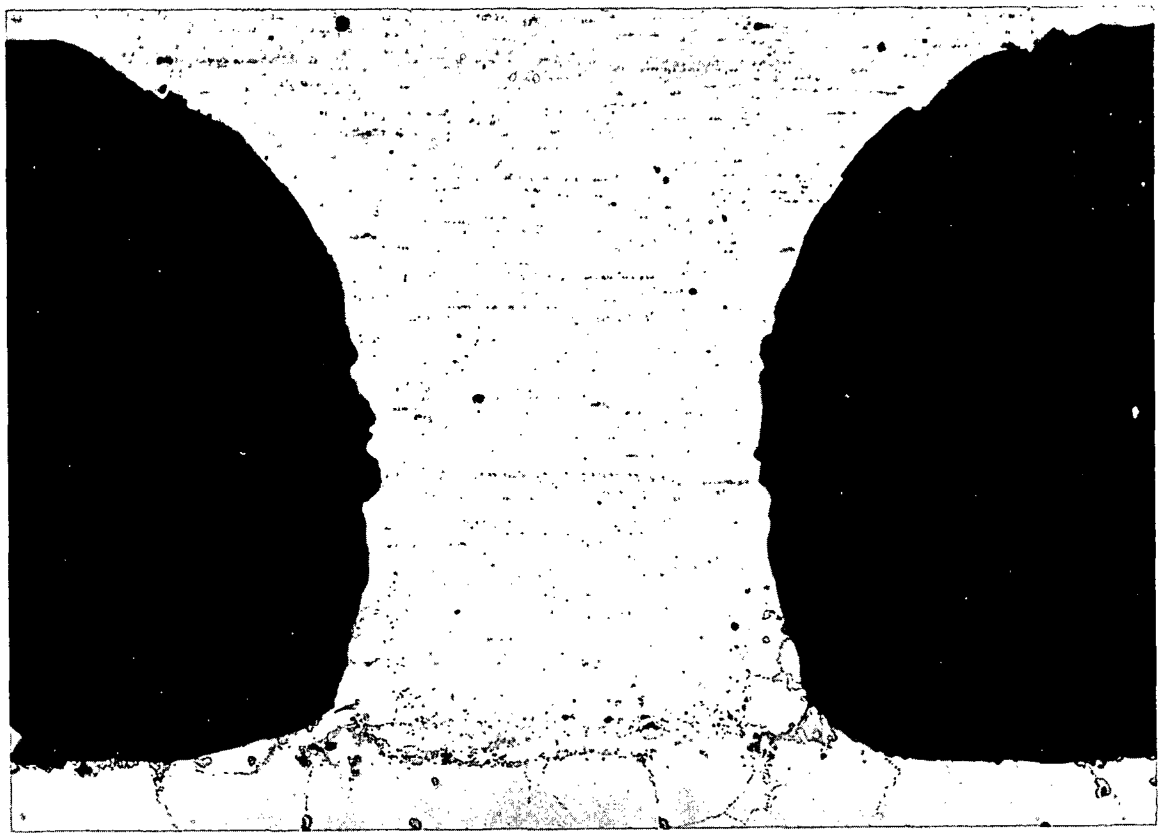


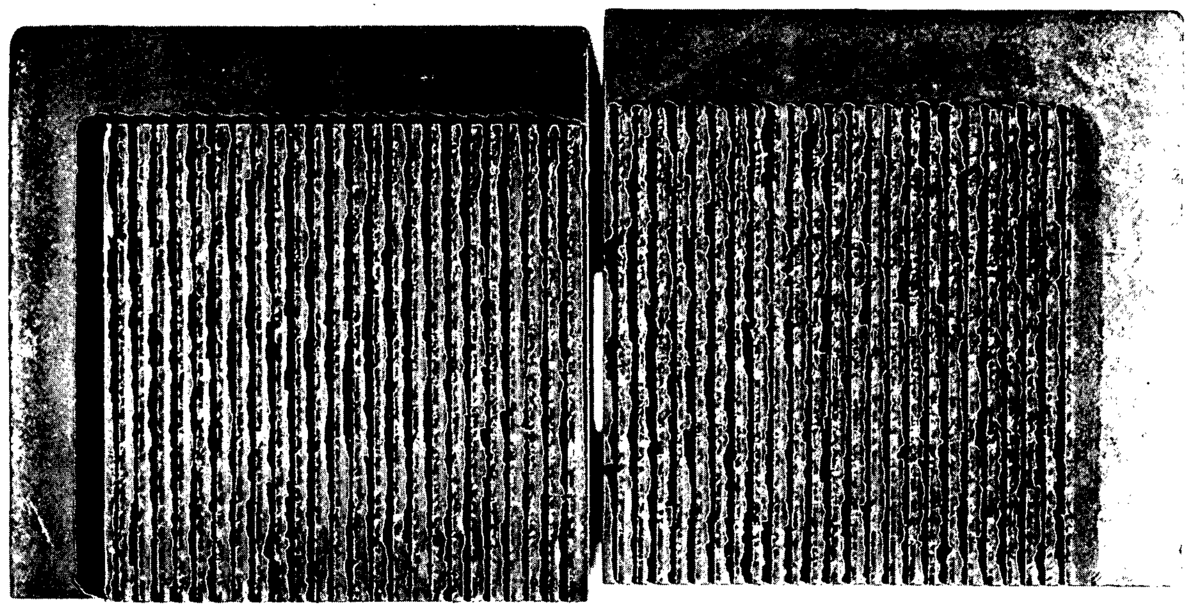
Figure 32. Stress Rupture Strength Versus Larson-Miller Parameter of Unexposed and Cyclic Exposed U700 - Rene' 80 Short Transverse Finned Specimens.



Neg. F9140 150X

Figure 33. Typical Finned Joint of a TDNiCr - Rene' 80 Short Transverse Finned Specimen.

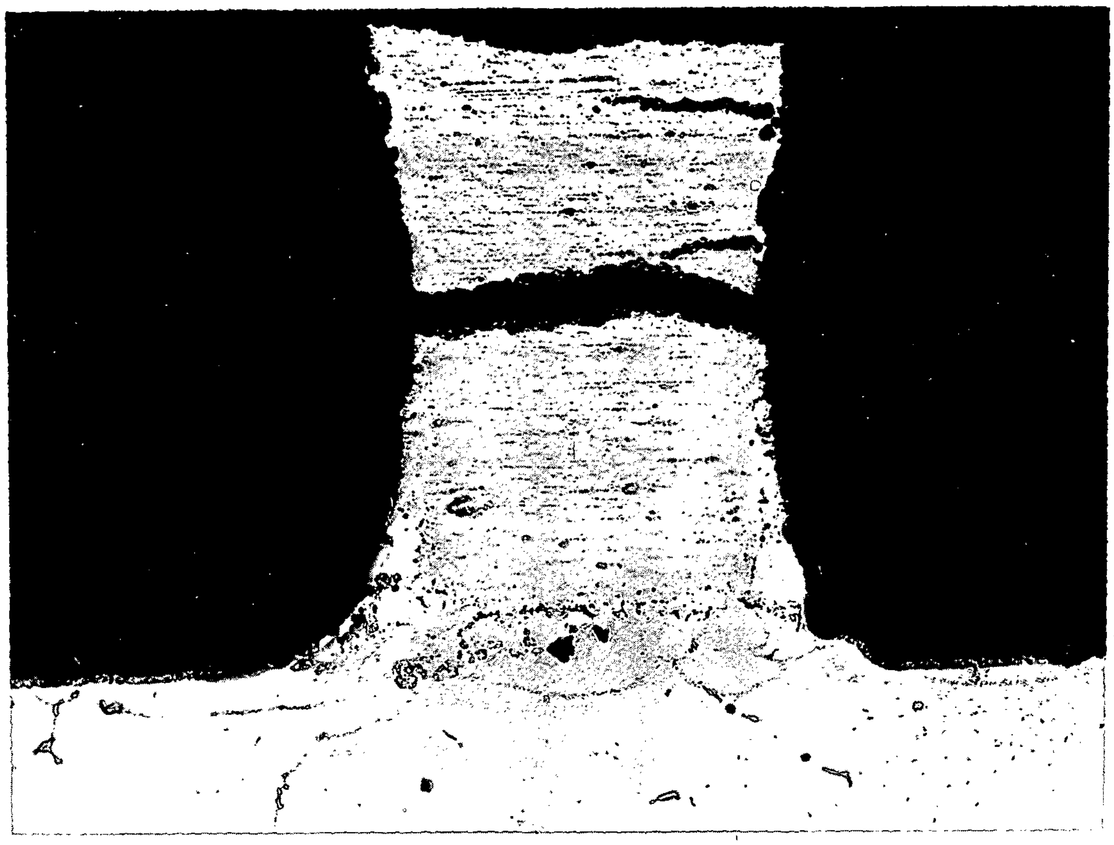
Note that the TDNiCr Fins are Still
Joined to the Rene' 80 Clevis Block



Neg. C70120914

2.5X

Figure 34. Typical Fin Failure of TDNiCr - Rene' 80 Short Transverse Finned Specimen.



Neg. F9144 100X

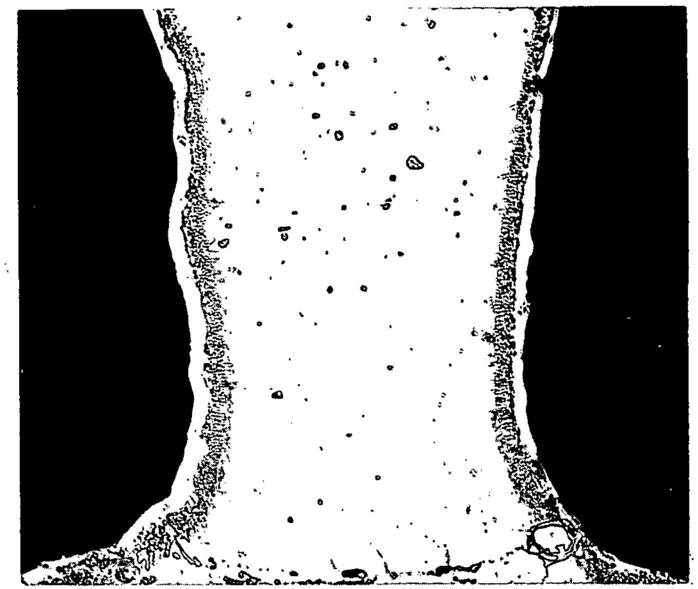
Figure 35. Typical Fin Failure of a TDNiCr - Rene' 80 Short Transverse Finned Specimen.

Neg. G0099 150X

Figure 36. Stress-Induced Thermally Accelerated Cracking of a of a TDNiCr Fin. Note the Severe Oxidation in the Cracks.

Neg. F9156 150X

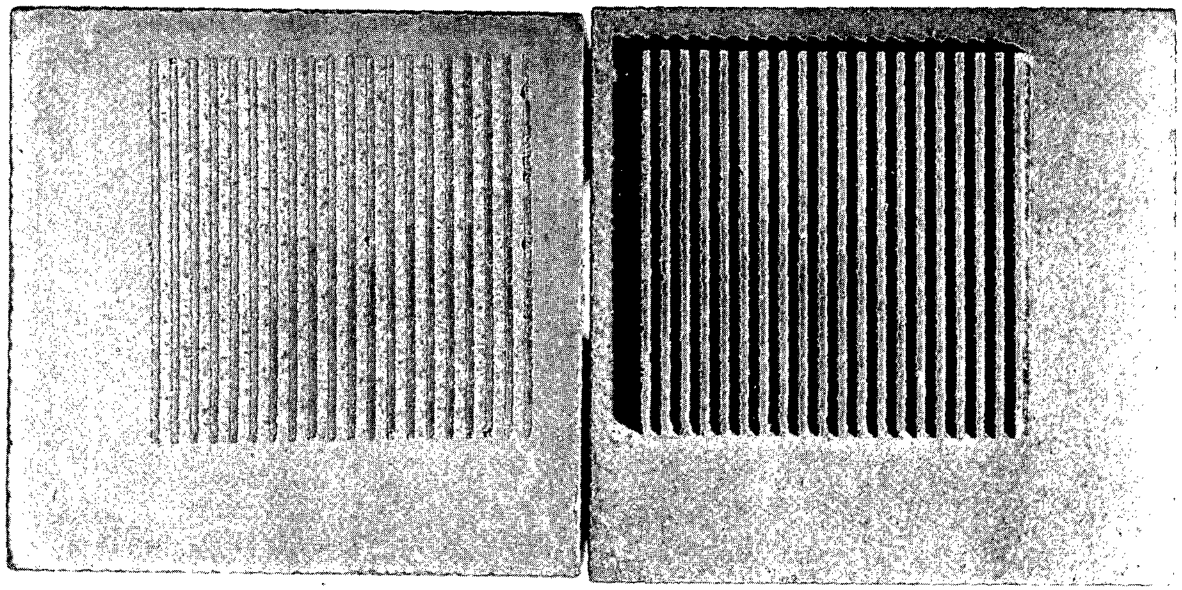
a. Uncoated



Neg. G6000 150X

b. Coated

Figure 37. Typical Finned Joint of a U700 - Rene' 80 Short Transverse Finned Specimen.



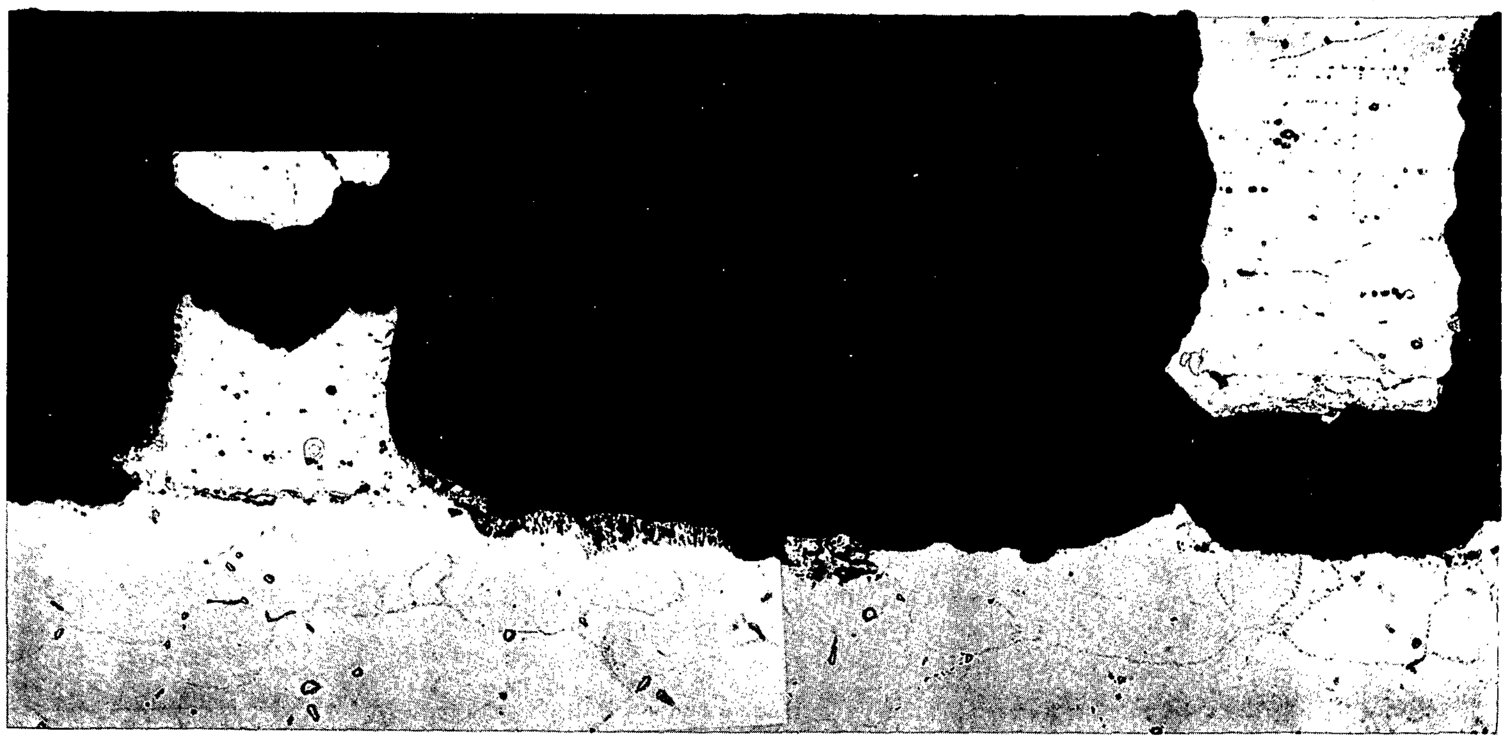
Neg. C70120911

2.5X

Figure 38. Typical Joint Failure of a U700 - Rene' 80 Short Transverse Finned Specimen.

Neg. F9154 150X

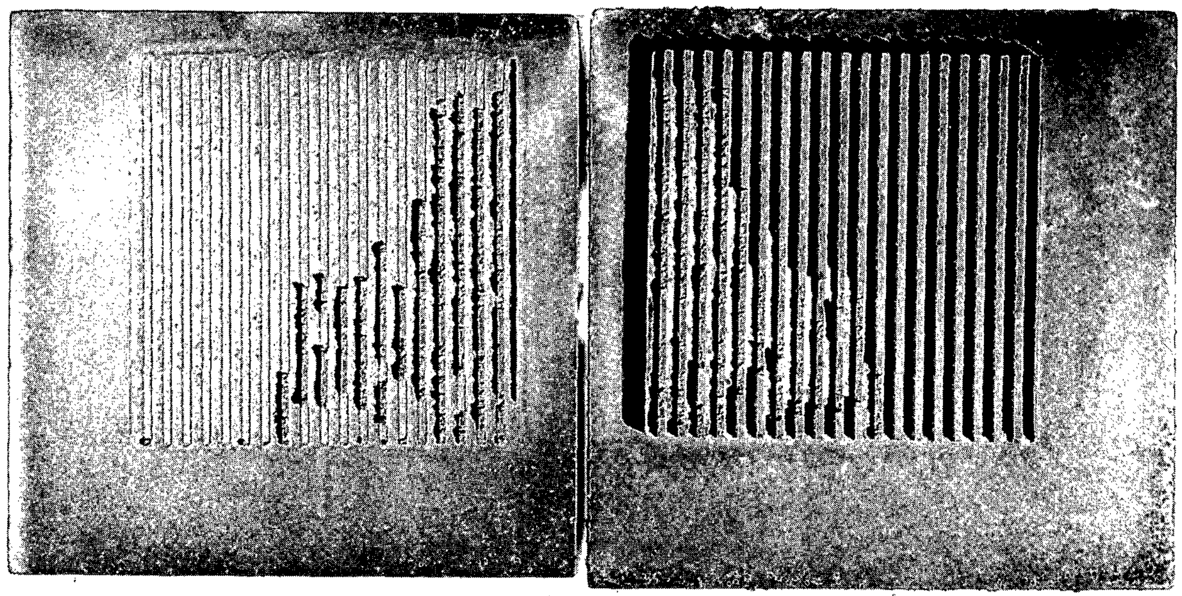
Figure 39. Typical Joint Failure of a U700 - Rene' 80 Short Transverse Finned Specimen.



Neg. F9166 100X

Figure 40. Combination Failure of U700 - Rene' 80 Short Transverse Finned Specimen.

Note that Some of the U700 Fins are
Still Joined to the Rene' 80 Clevis Block



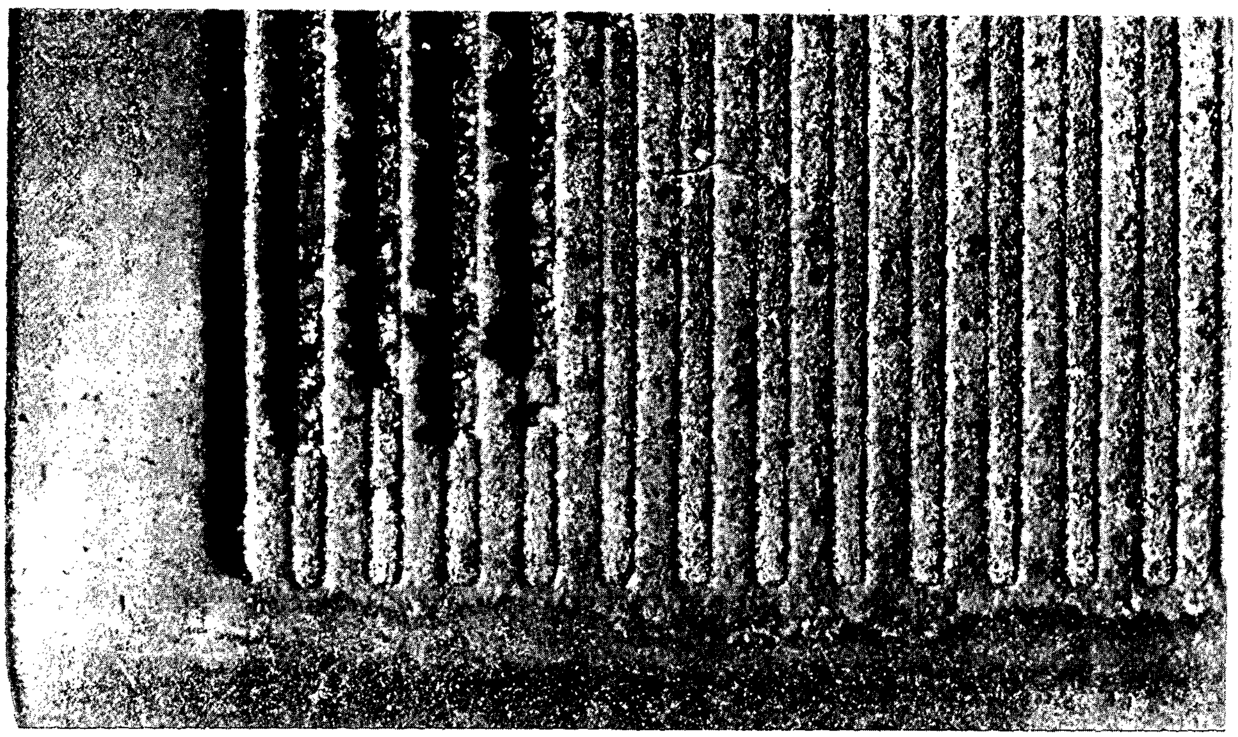
Neg. C70120912

2.5X

Figure 41. Combination Failure of a U700 - Rene' 80 Short Transverse Finned Specimen.

Note that Some of the U700 Fins are Still Joined to the Rene' 80 Clevis Block

Note that the B-1 Brazing Alloy Fillets Remain Joined to the Rene' 80 when a Joint Failure Occurs



Neg. C70120923 10X

Figure 42. Enlargement of Figure 40 Combination Failure of a U700 - Rene' 80 Short Transverse Finned Specimen.

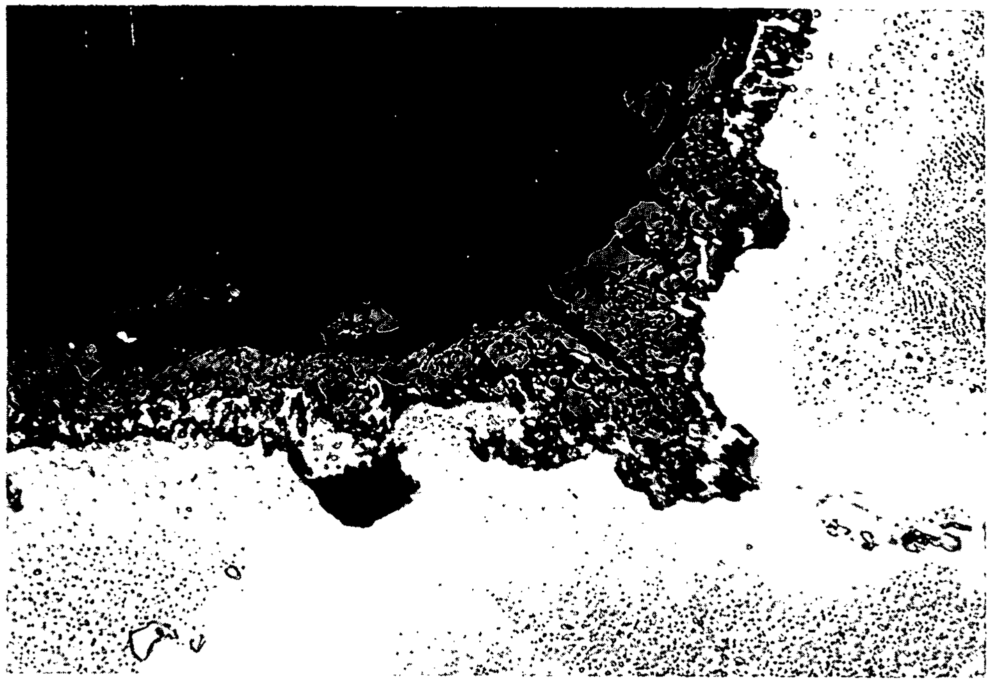
Neg. F9160 100X

a. Uncoated.

Neg. G6002 150X

b. Coated.
(Note the lack of oxidation)

Figure 43. Typical Oxidation due to Cyclic Exposure of a U700 - Rene' 80 Short Transverse Finned Specimen.



Neg. F9212 500X

Neg. F9161 100X

Figure 44. Gross Oxidation Occassionally Encountered in Cyclic Exposed U700 - Rene' 80 Short Transverse Finned Specimens.

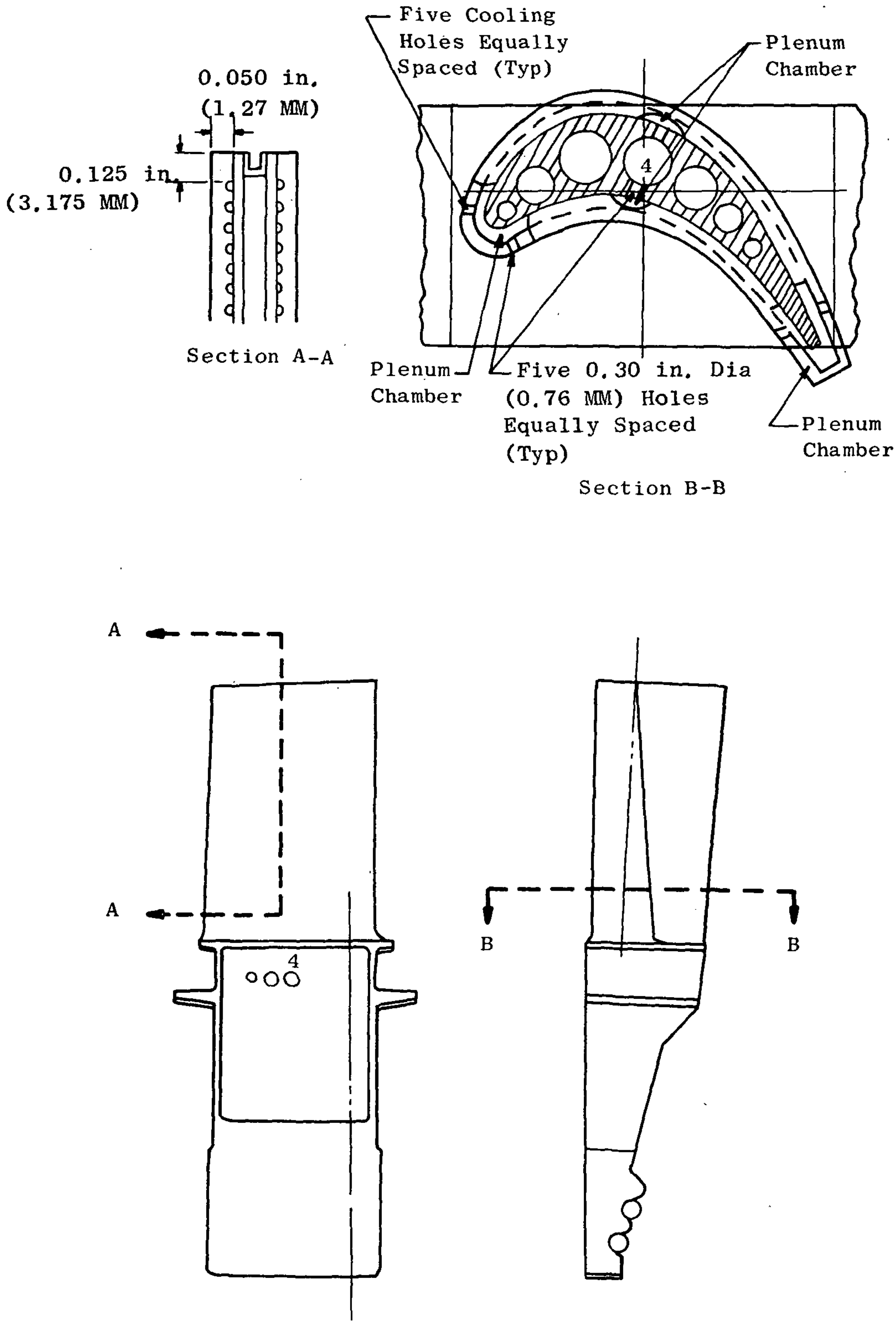
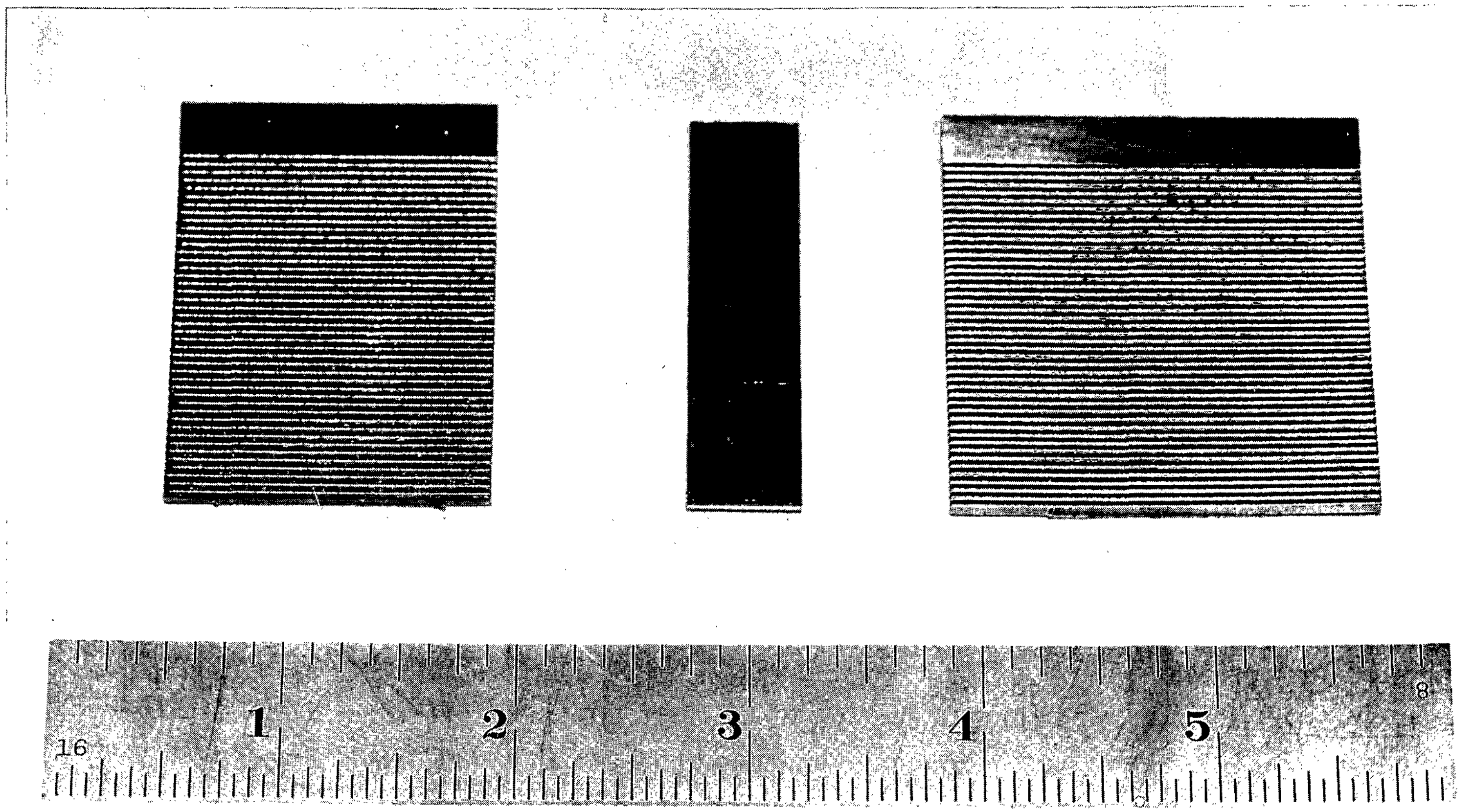
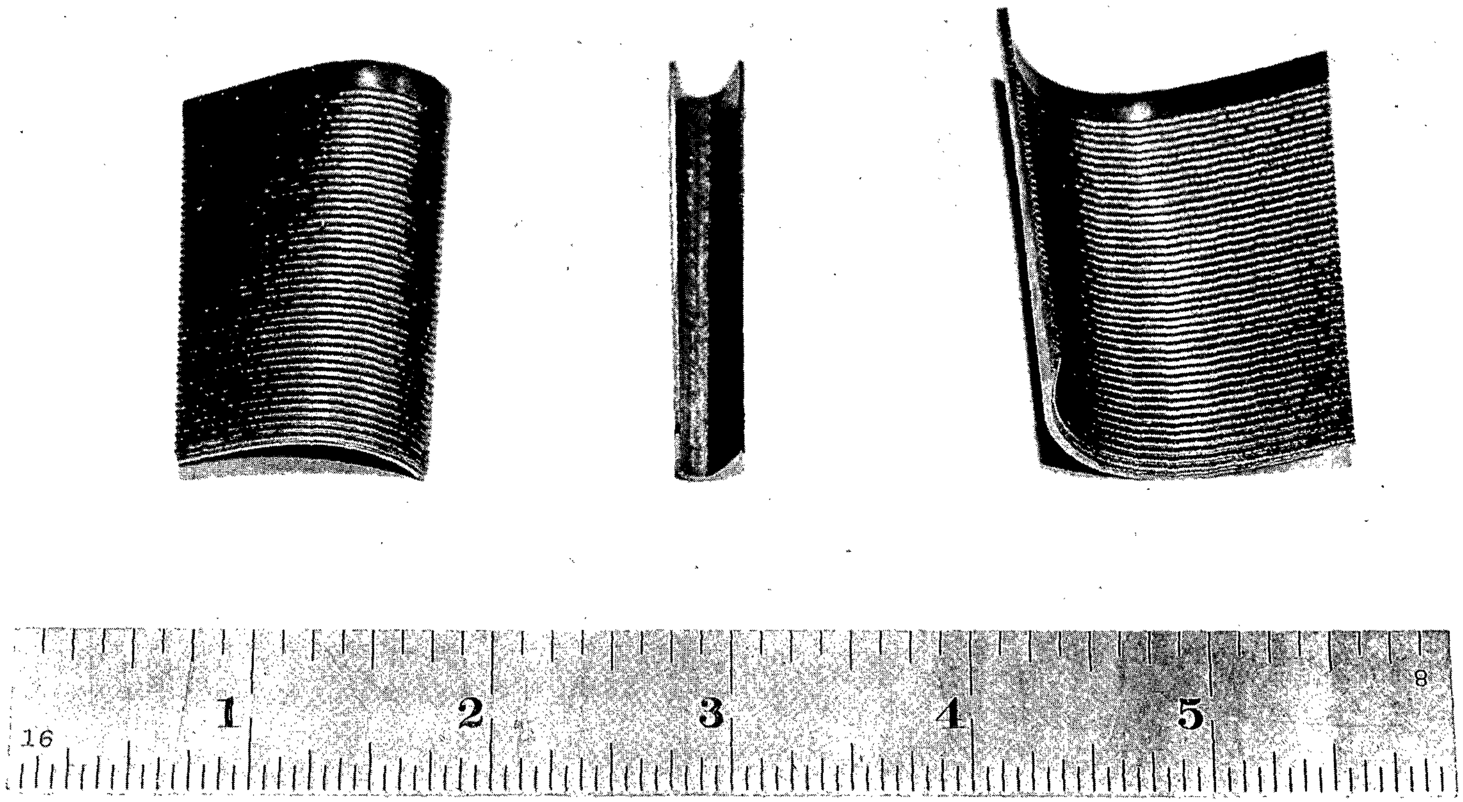


Figure 45. Basic Blade and Finned Shell Configuration.



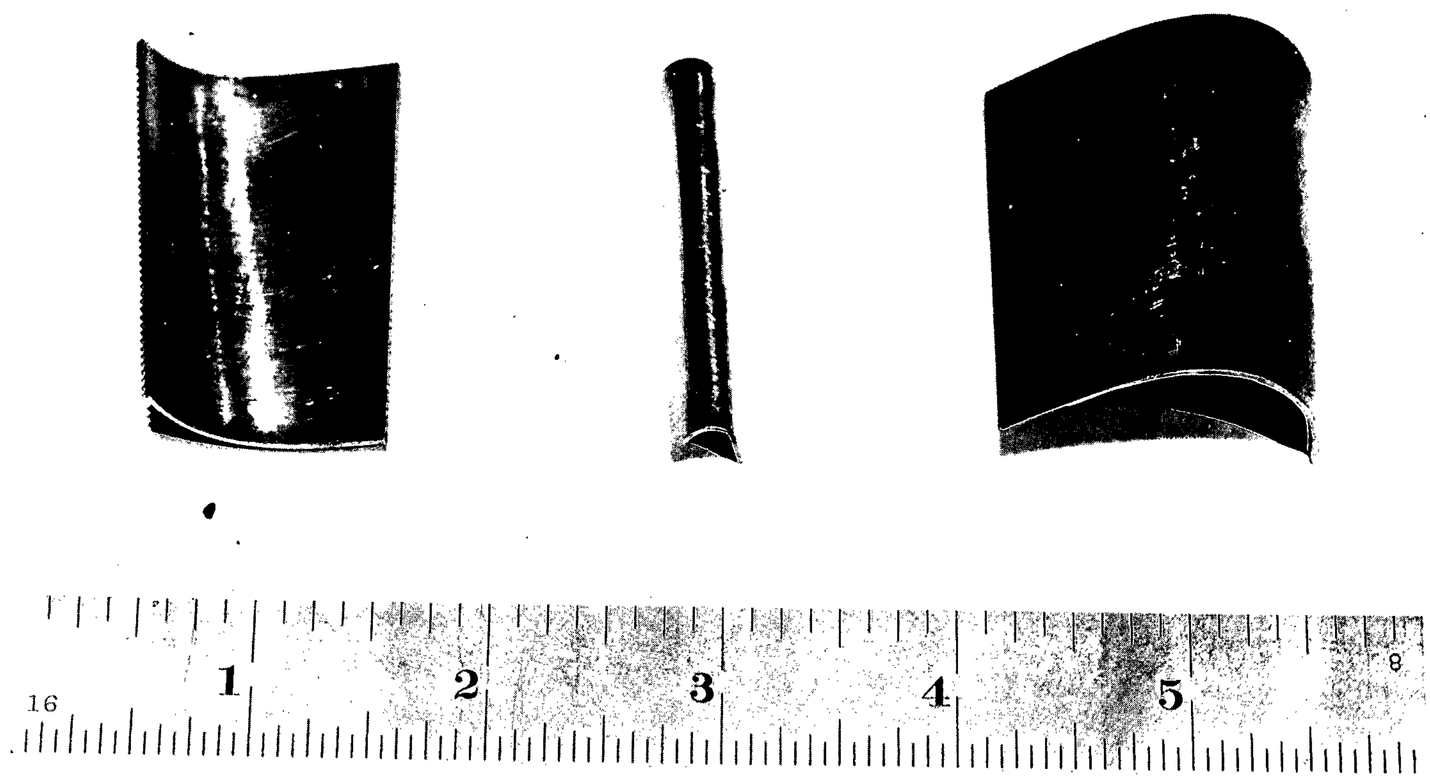
Neg. C70100603

Figure 46. Finned Shell Blanks Prior to Forming.



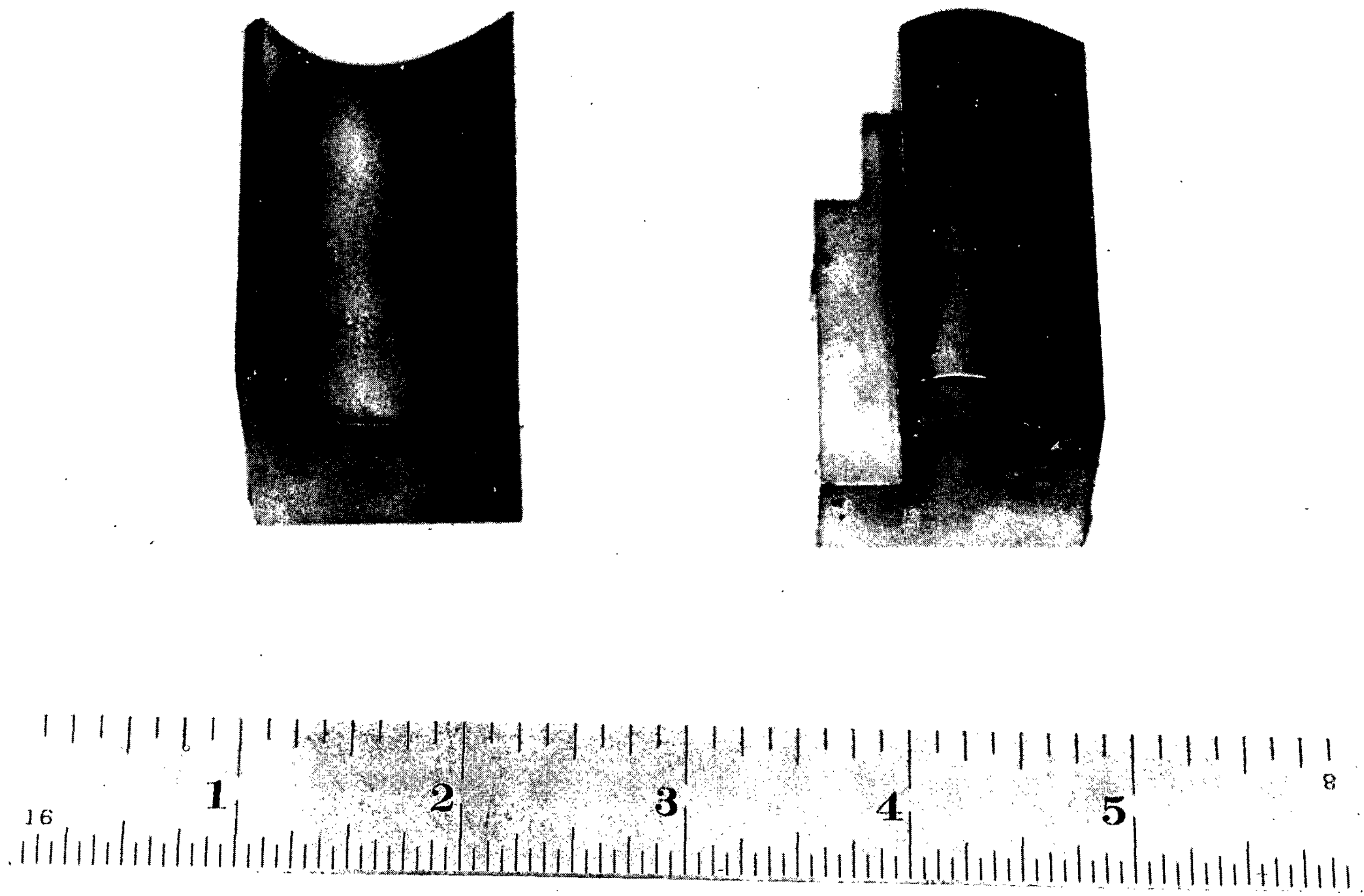
Neg. C70100604

Figure 47. Interior Surfaces of Finned Shells After Forming.



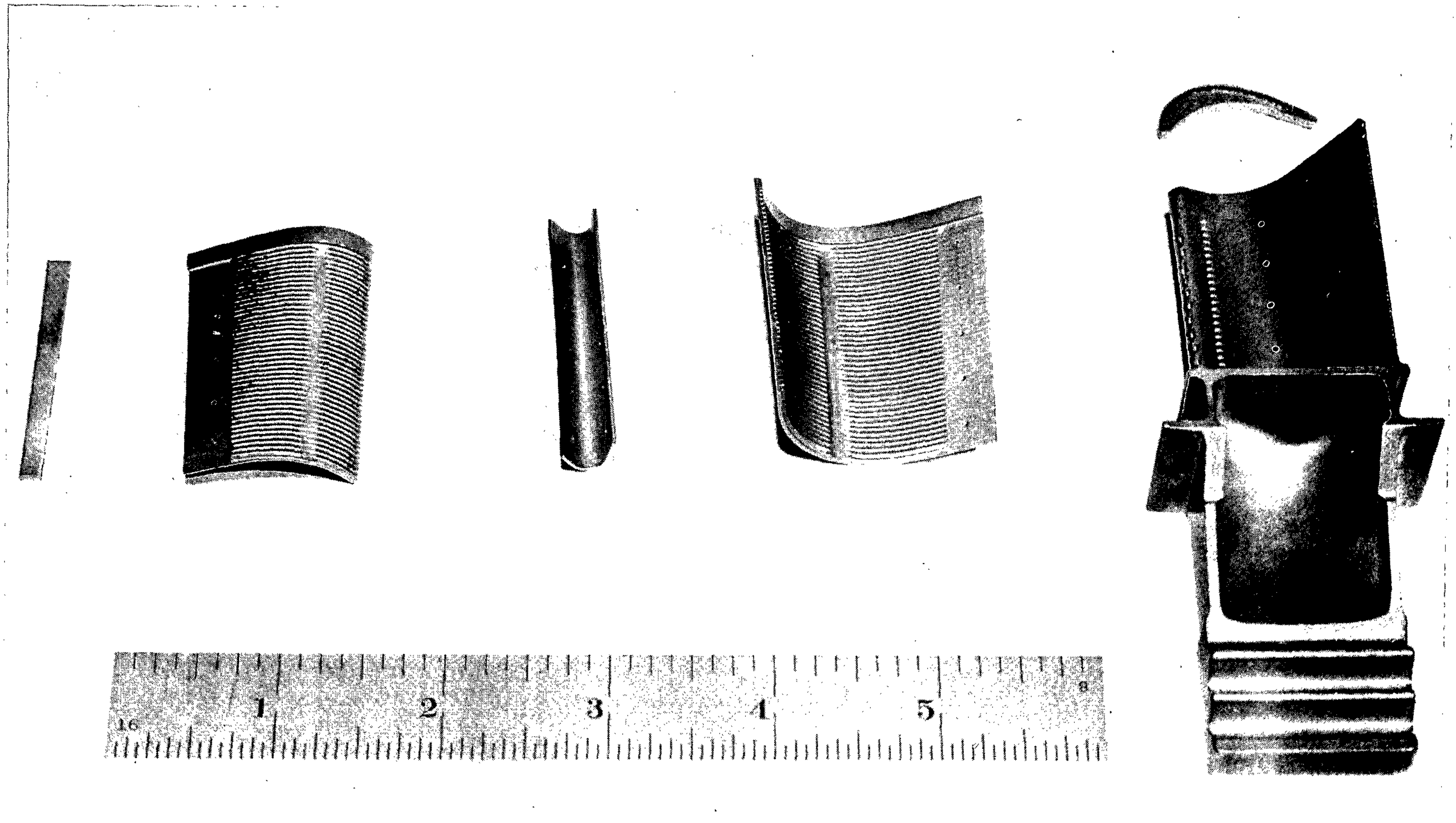
Neg. C70100605

Figure 48. Exterior Surfaces of Finned Shells After Forming.



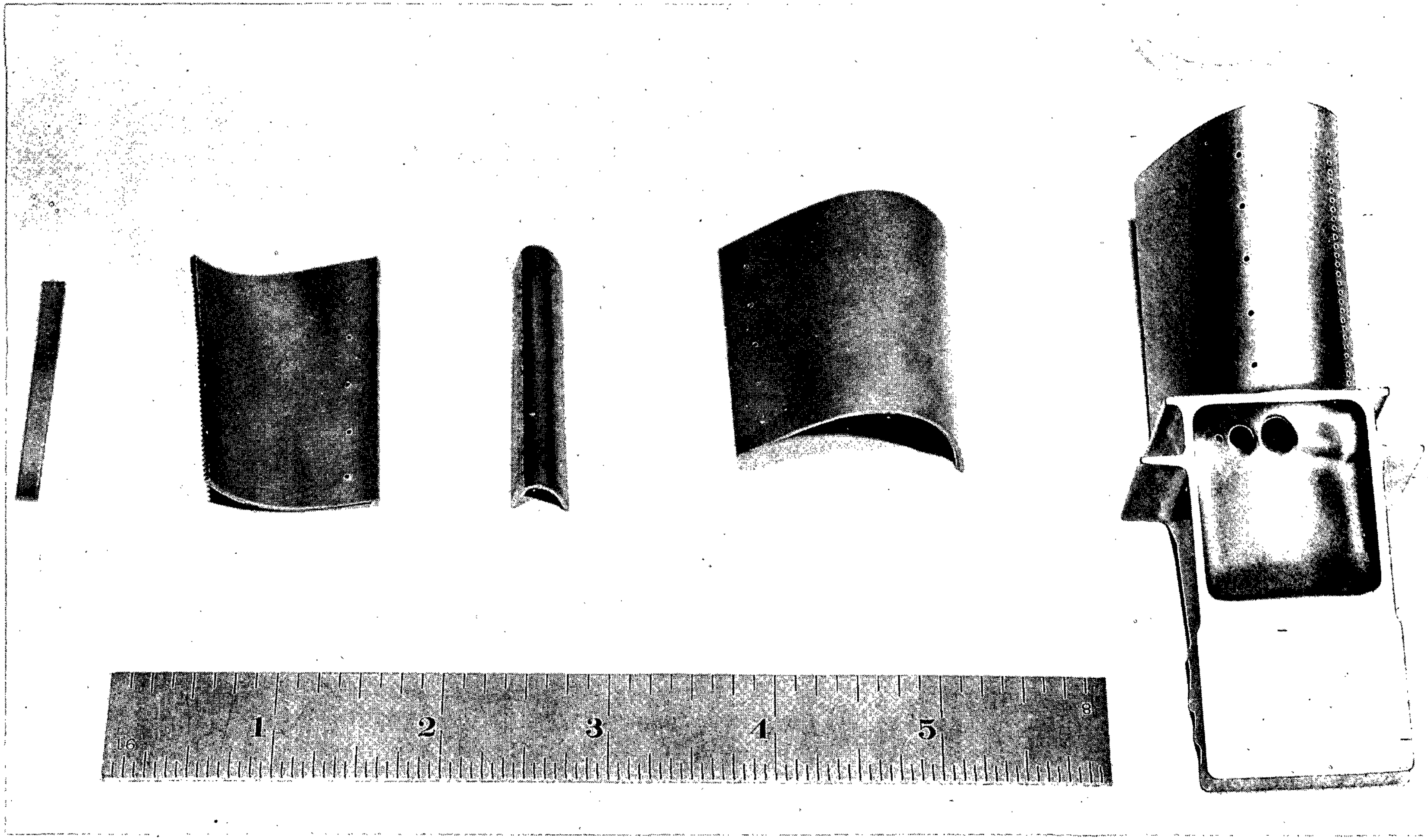
Neg. C70100606

Figure 49. First Pair of Activated Diffusion Brazing Dies.



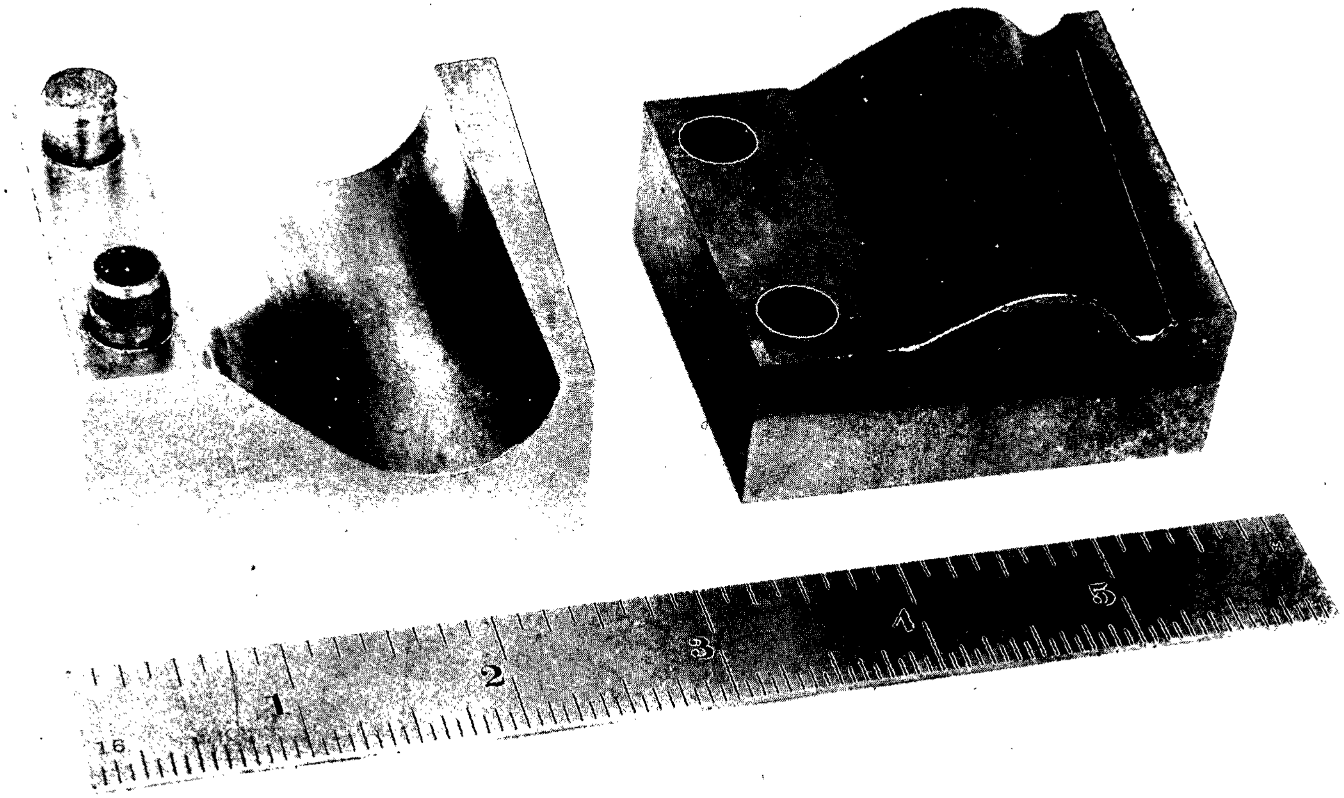
Neg. C70100601

Figure 50. Interior Surfaces of Finned Shells and Blade Prior to Activated Diffusion Brazing.



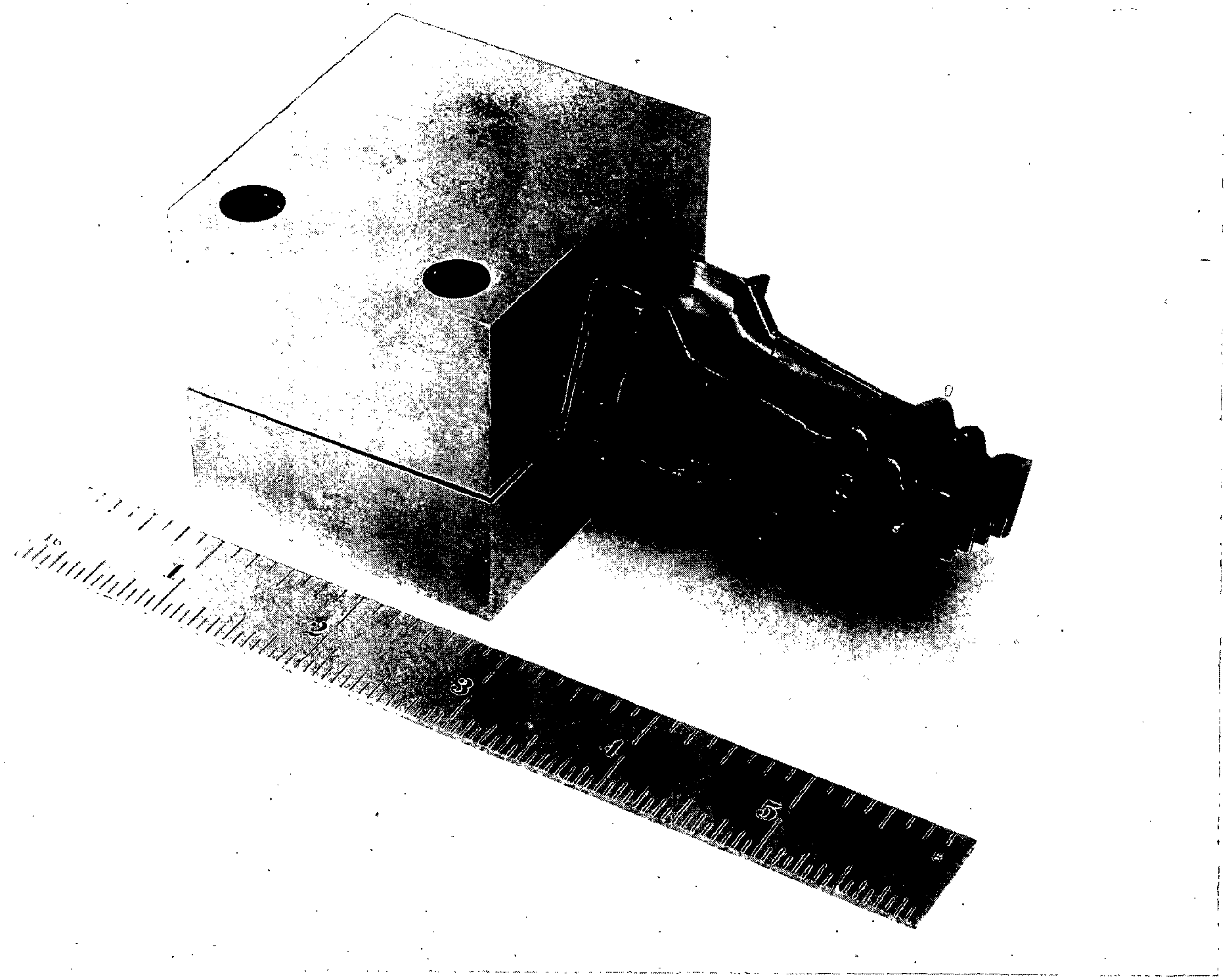
Neg. C70100602

Figure 51. Exterior Surfaces of Finned Shells and Blade Prior to Activated Diffusion Brazing.



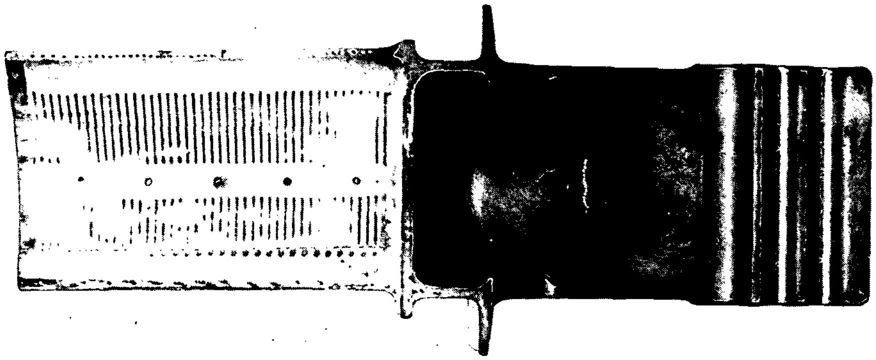
Neg. C70100980

Figure 52. Second Pair of Activated Diffusion Brazing Dies.

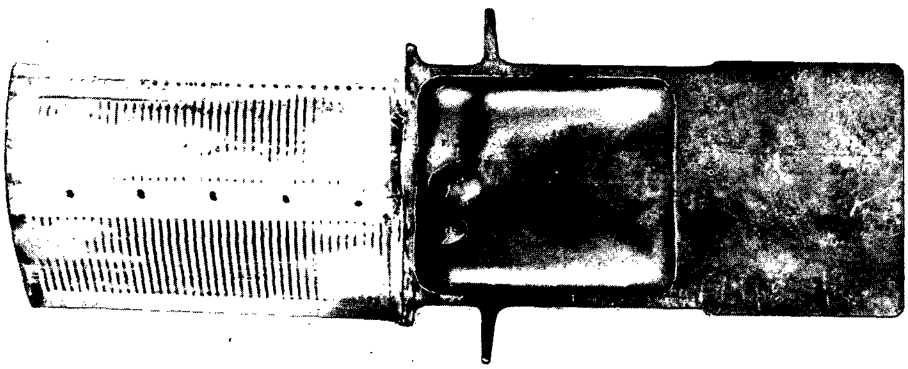


Neg. C70100979

Figure 53. Blade and Shells Assembled in Activated Diffusion Brazing Dies.

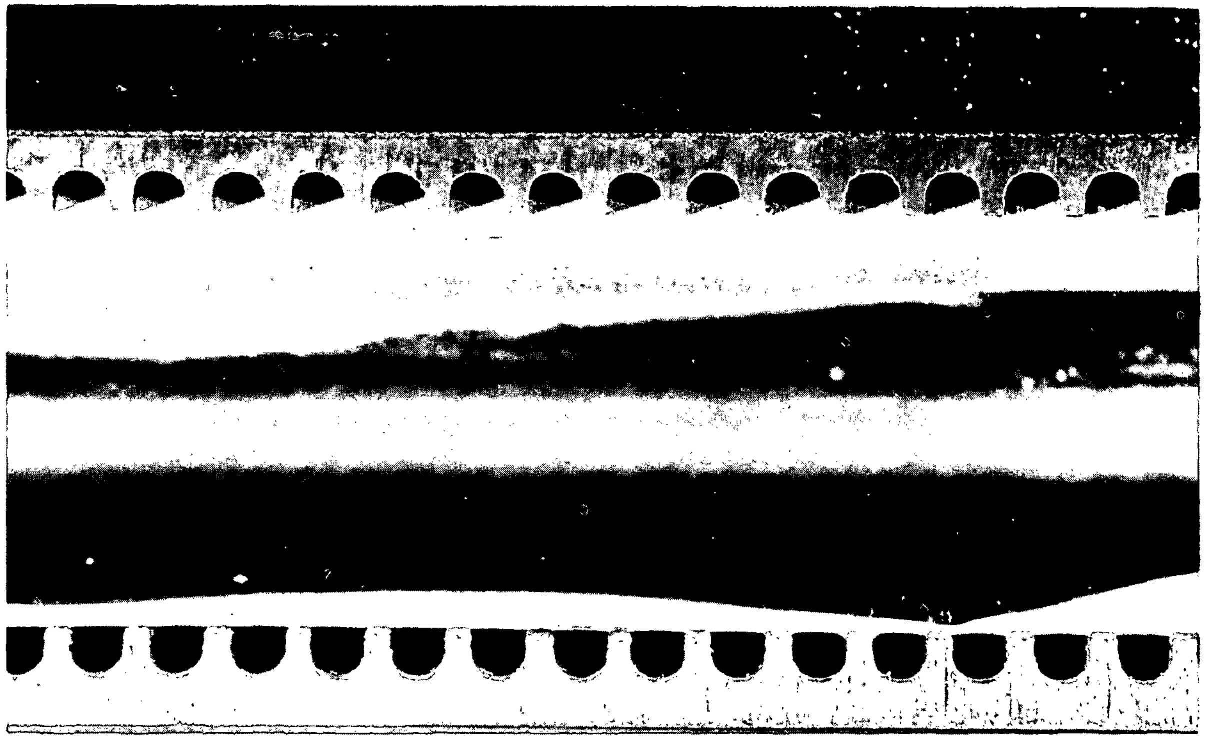


Neg. C70102027 Pressure Face



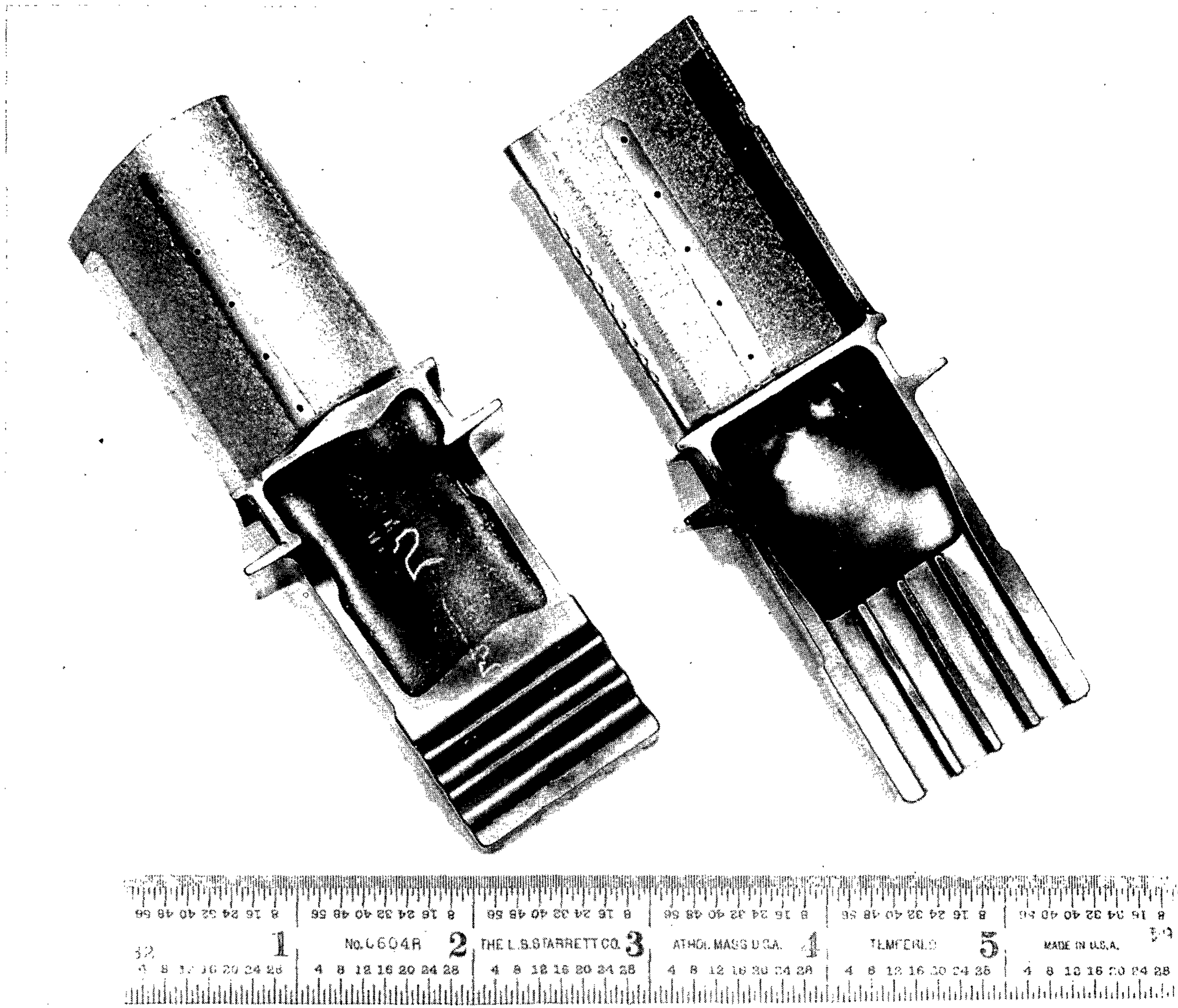
Neg. C70102028 Suction Face

Figure 54. Impressions Obtained in YO_2 Stop-Off Compound After Creep Forming.



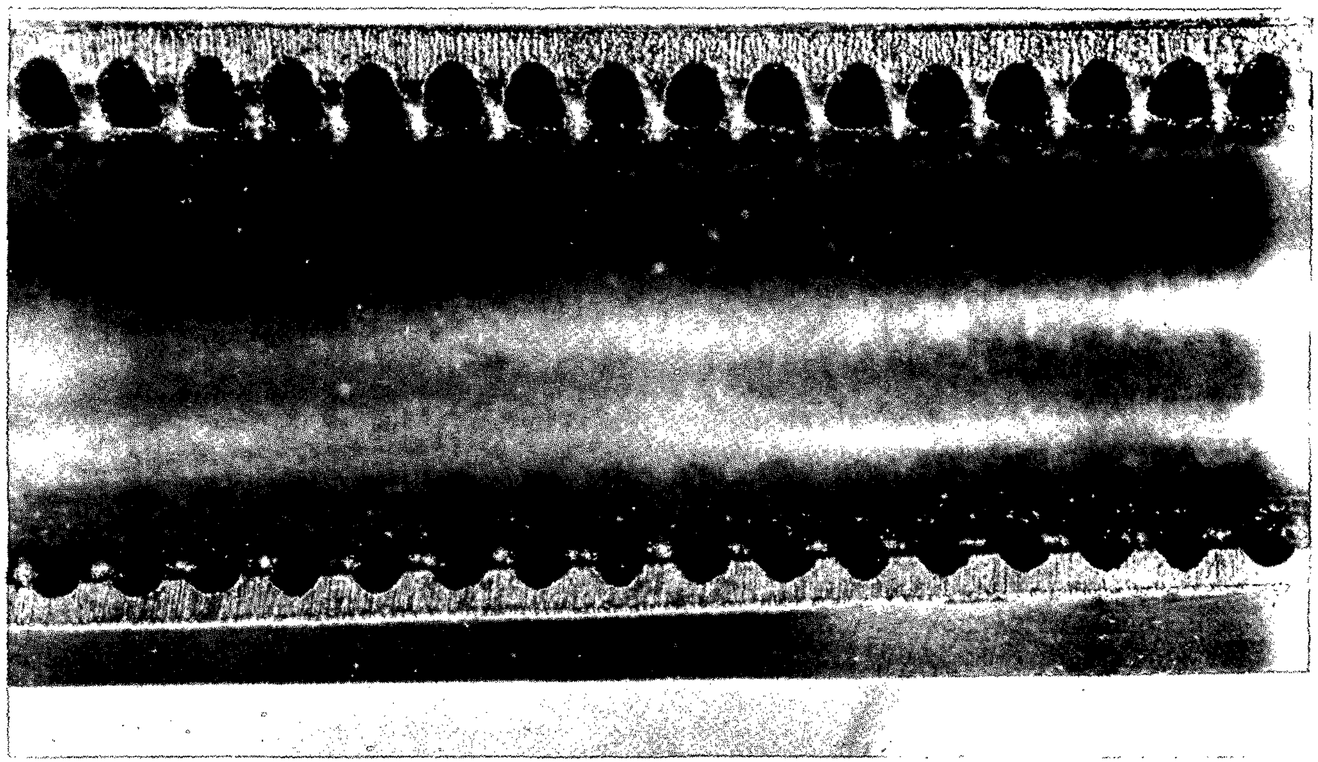
Neg 318139 10X

Figure 55. Leading Edges of Pressure Face and Suction Face Finned Shells After Creep Forming.



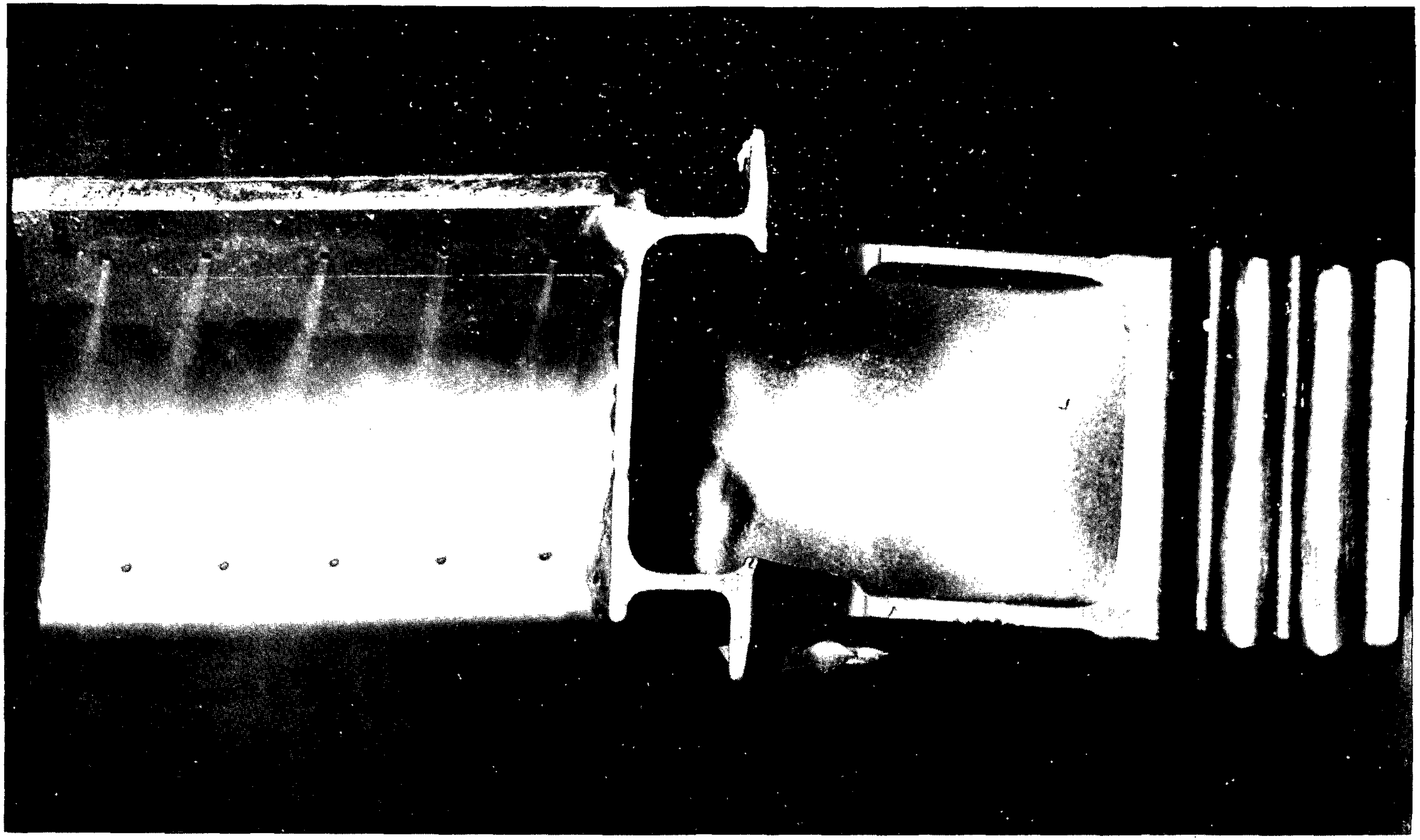
Neg. 318140

Figure 56. Suction and Pressure Faces of Blade with B-1 Alloy Plasma Sprayed on the Surfaces.



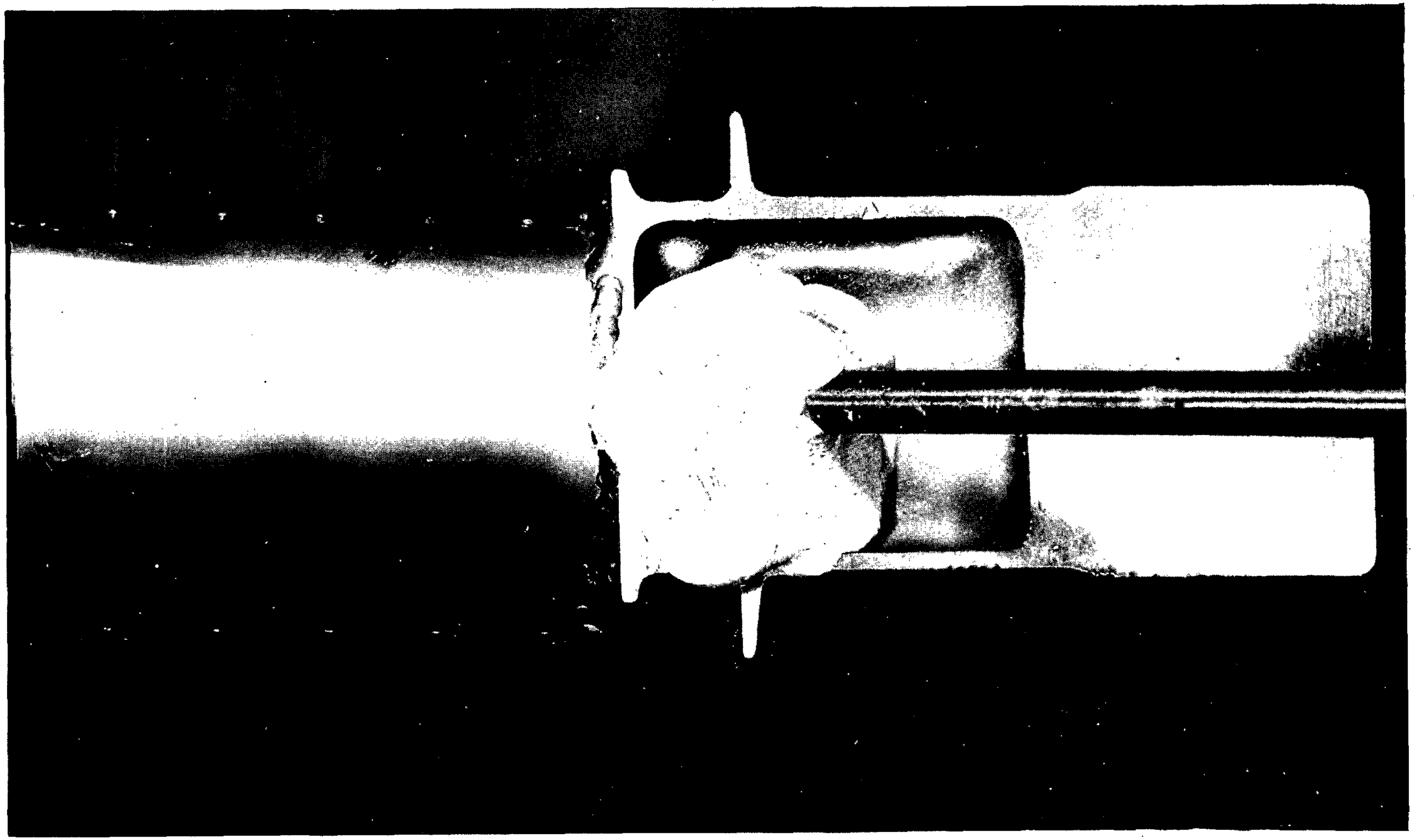
Neg. C70121129 10X

Figure 57. Filleting Obtained at Leading Edges of Pressure and Suction Faces of Finned Shells After Activated Diffusion Brazing.



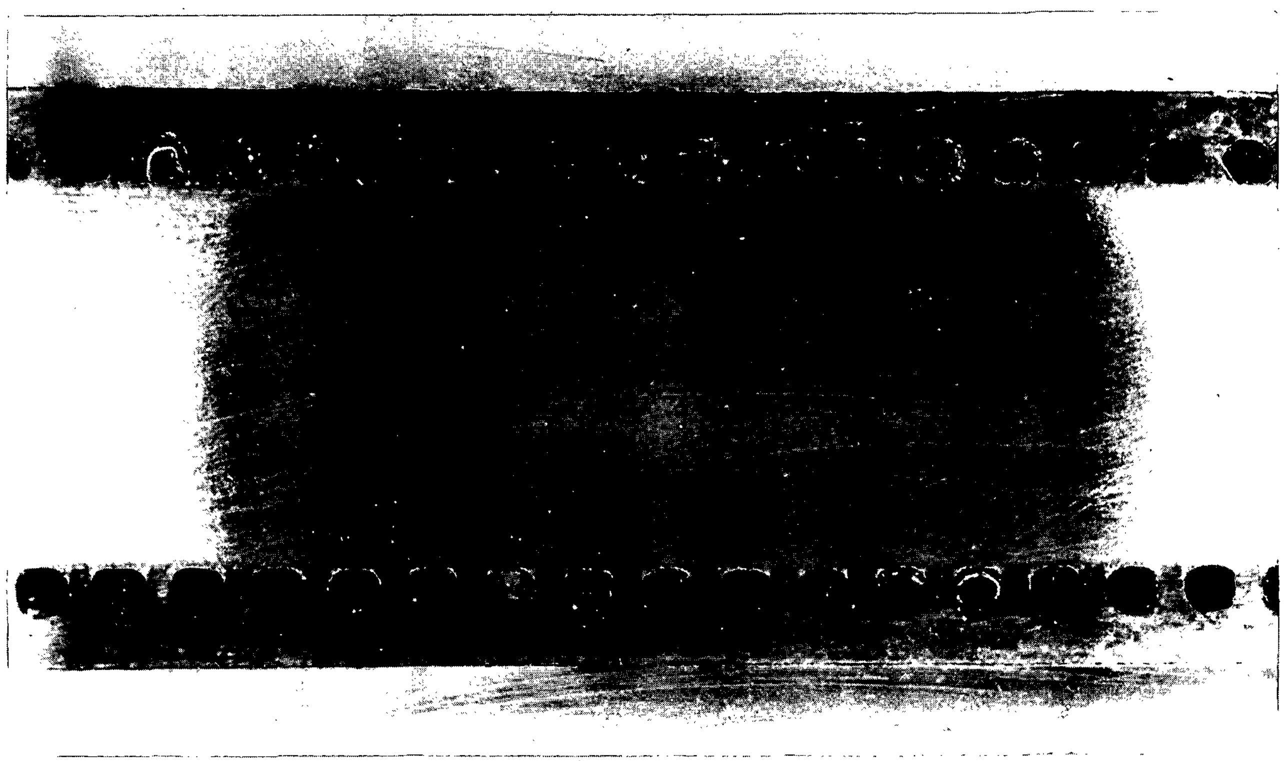
Neg. 318143 2X

Figure 58. Pressure Face of Activated Diffusion Brazed Blade. Note that Smoke is Being Emitted Out of the Bleed Holes.



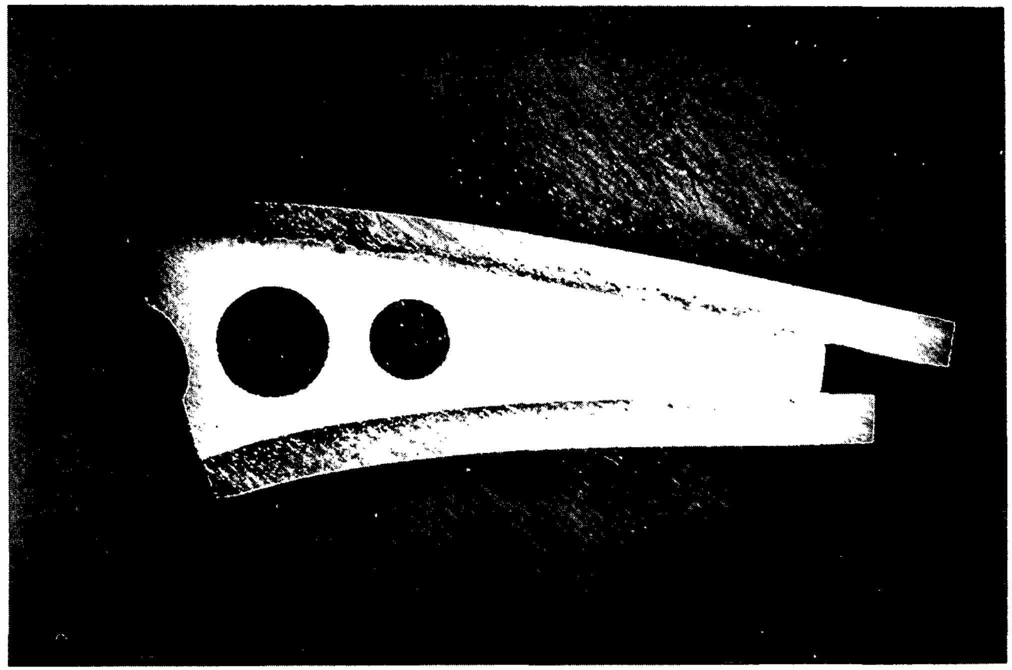
Neg. 318142 2X

Figure 59. Suction Face of Activated Diffusion Brazed Blade. Note that Smoke is Being Emitted Out of the Bleed Holes.



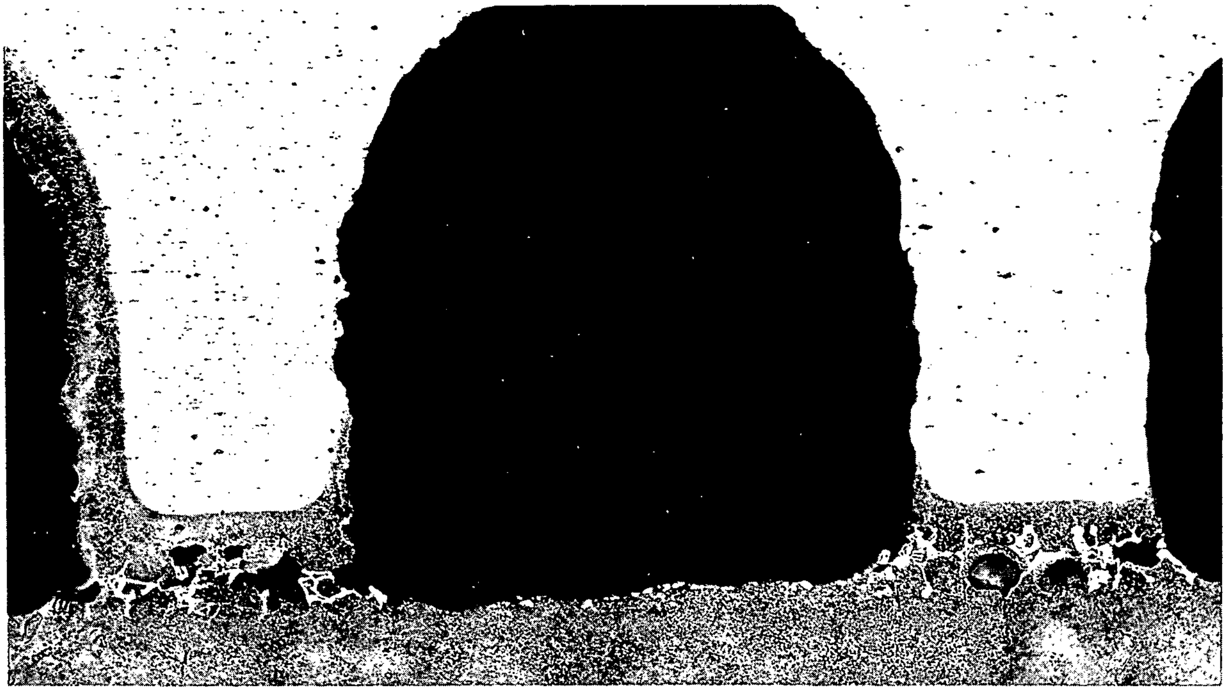
Neg. C70121132 10X

Figure 60. Radial Section Through Pressure and Suction Face Shells After Activated Diffusion Brazing.

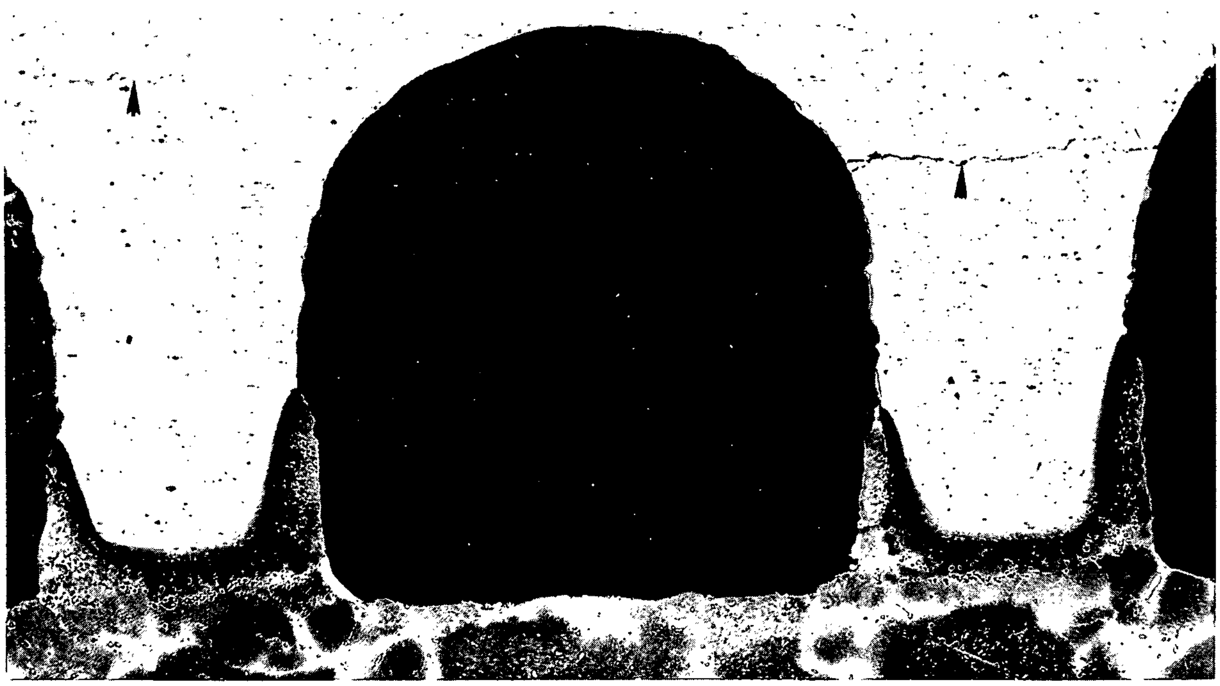


Neg. C70121133 5X

Figure 61. Axial Section Through Pressure and Suction Face Shells After Activated Diffusion Brazing.

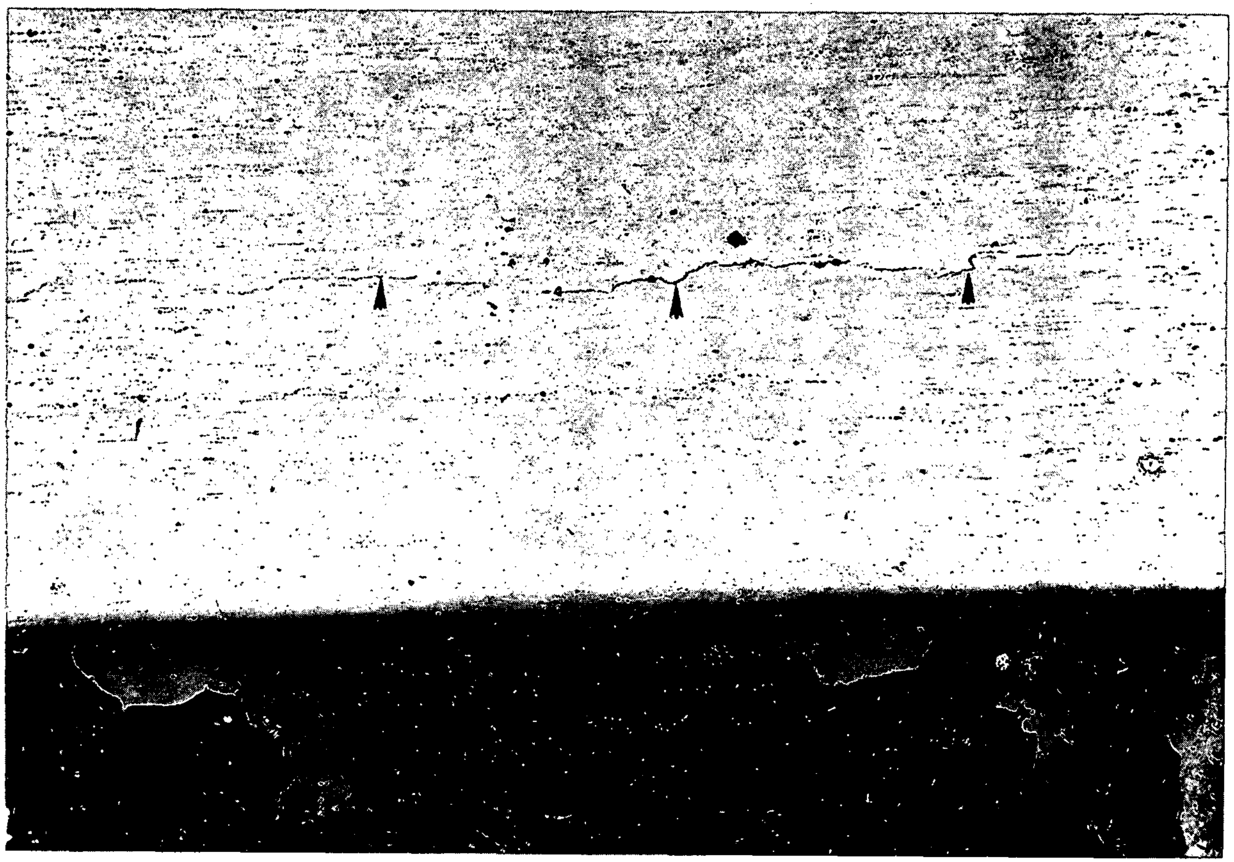


Neg. F9385 Crack Free, Showing Voids 100X



Neg. F9383 Containing Cracks 100X

Figure 62. Transverse Sections Through Finned TDNiCr Shell After Activated Diffusion Brazing Using B-1 Transfer Tape Alloy. Note Cracking Denoted by Arrows.

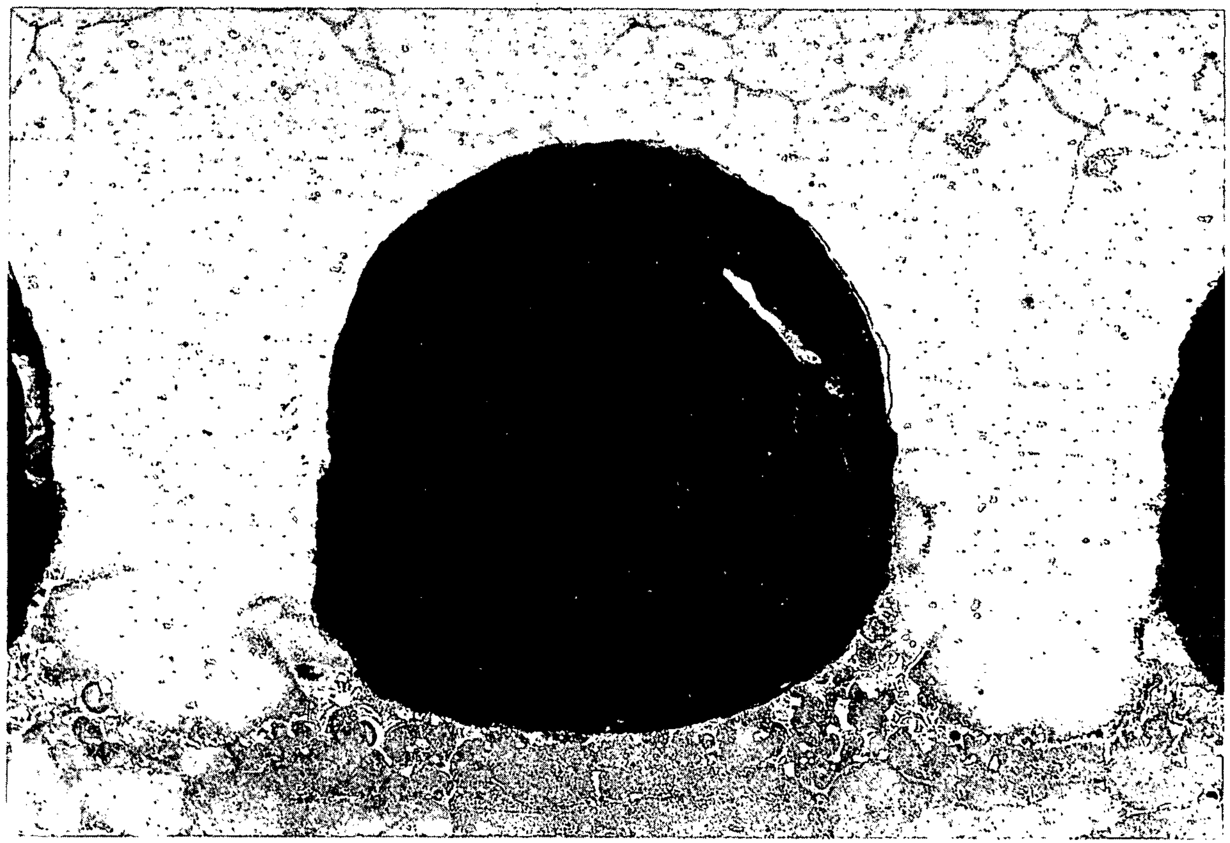


Neg. F9386 100X

Figure 63. Axial Section Through a Cracked TDNiCr Fin After Activated Diffusion Brazing with Plasma-Sprayed B-1 Alloy. Note Cracking Denoted by Arrows.

Neg. F9384 100X

Figure 64. Transverse Section Through TDNiCr Finned Shell After Activated Diffusion Brazing with Plasma-Sprayed B-1 Alloy.



Neg. F9381

100X

Figure 65. Transfer Section Through U700 Finned Shell After Activated Diffusion Brazing with Plasma-Sprayed B-1 Alloy.

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