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DEVELOPMENT OF EXPLOSIVE-WELDING TECHNIQUES FOR FABRICATION OF REGENERATIVELY COOLED THRUST CHAMBERS FOR LARGE-ROCKET-ENGINE REQUIREMENTS

by

E. G. Smith, Jr., D. Laber, V. D. Linse,
and M. J. Ryan

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Contract NAS3-10306

June 15, 1971

BATTELLE
COLUMBUS LABORATORIES

FINAL REPORT

on

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NASA-Lewis Research Center
Cleveland, Ohio
John M. Kazaroff
Chemical Rockets Division

FOREWORD

The research described herein was conducted by Battelle's Columbus Laboratories, Materials Design and Fabrication Division, from June 28, 1967, to September 15, 1970, and performed under NASA Contract NAS3-10306. The work was conducted under the management of NASA Project Manager, John M. Kazaroff, Chemical Rockets Division, NASA-Lewis Research Center.

The authors acknowledge contributions of several individuals to the research work described in the report. The plasma-spray experiments and oxide-coating preparation was performed by Mr. R. L. Heestand. The fusion-welding studies in the preparation of the Allvac 718 shell structure for the cylindrical spoolpiece were conducted by Mr. D. L. Cheever. During the latter portion of the program, Mr. R. L. Martin contributed substantially to the explosive welding studies, particularly the preparation and completion of the stainless steel/Hastelloy X spoolpiece.

The data generated during the program are recorded in Book Nos. 25103, 25170, 25537, 25951, 26640, and 27454.

ABSTRACT

Explosive welding was investigated as a new technique for fabricating regeneratively cooled rocket-motor thrust chambers. The process developed consisted of the explosive welding of the ribs to the outer shell and the inner liner to the ribs to form the desired coolant channels in flat-panel specimens, cylindrical spoolpieces, and complex-shaped thrust-chamber segments. Techniques for evaluating the explosive-welded channel structures included metallography, ultrasonic inspection, hydrostatic proof testing and burst testing.

PROGRAM SUMMARY

During the Task I studies, explosive-welding techniques were developed for fabricating a flat-panel section whose cross-section configuration was typical of a regeneratively cooled rocket-engine thrust chamber. Two welding operations were used in fabricating the panel section. The rib and shell components were welded in one operation, while the liner and rib components were welded in a second operation.

The explosive-welding parameters for the material combinations of interest were established in preliminary experiments during which weld properties and welding effects on material properties were also determined. Fabrication procedures were developed for three-rib panels and then used to fabricate six- and nine-rib panel specimens. Both nondestructive and destructive tests were employed to verify the integrity of their rib-to-shell and liner-to-rib welds at various stages of fabrication.

Panel specimens consisting of Type 304 stainless steel ribs and shells with Hastelloy X liners, and specimens consisting of Allvac 718 ribs and shells with either Hastelloy X or Allvac 718 liners were successfully fabricated. Several of these panel specimens were tested at pressures of several times the 500-psi proof-test level without failure.

The objective of Task II was to apply the explosive-welding technology developed in Task I to the fabrication of channeled cylindrical spoolpieces. The task was conducted in two phases. During the first phase, the procedures and parameters required for the three explosive welding operations needed to fabricate the complete spoolpieces were developed, and during the second, the techniques developed were applied to the fabrication of two spoolpieces.

One of the two spoolpieces required was fabricated and shipped to NASA-Lewis for test firing. This chamber consisted of a Type 304 stainless steel shell, plenum, and ribs, and Hastelloy X liner and end covers. Two important factors contributed to the successful fabrication of this chamber. One was the initial use of a thick-wall cylinder for the shell and plenum sections, which avoided several problems associated with fabricating these components separately and joining them. The other factor was the use of an integral, rather than a split, die to support the shell during the rib-welding operation.

The second prototype thrust chamber, consisting of Allvac 718 shell, plenum, and ribs, and Hastelloy X liner and covers, was not completed because of problems encountered in fabricating the shell and plenum components and in welding the ribs to the shell. The shell and plenum components of this chamber were fabricated separately and joined by fusion welding. Several problems were encountered in these fusion-welding operations. After two attempts to weld the components and several explosive sizing steps, the shell-plenum part of the chamber was successfully made to the required size. A split die was used to support this chamber during the rib-to-shell welding operation but did not provide the required restraint during welding and the shell was damaged severely. This welding operation developed cracks in and around the longitudinal and girth welds and badly distorted the shell. This damage precluded the successful fabrication of the second spoolpiece. In its place, a cylindrical Allvac 718/Hastelloy X segment, fabricated earlier in Task II, was leak checked and pressure tested and forwarded to NASA-Lewis for evaluation.

The objective of Task III was to demonstrate the feasibility of using explosive welding to fabricate rib-channelled rocket-nozzle segments. In this task, the technical problems associated with welding to a complex curvature were examined both abstractly (without reference to a particular component) and practically (in attempts to fabricate sample ribbed segments). This task drew extensively on the results of Tasks I and II for welding parameters, tooling configurations, and other pertinent process details.

This task was conducted in three phases. In the first, components required for the welding experiments were fabricated. This was a major effort, and in it, techniques were developed for explosively forming stainless steel nozzles from commercially available thick-wall pipe. Explosive forming methods were also developed to form 70-degree segments of the required nozzle configuration from Alloy 718 and Hastelloy X sheet stock.

During the second phase the explosive-welding behavior of simulated and actual nozzle components was examined. In the simulated-component experiments, various problems associated with welding of the nozzle segments were examined. Several of these experiments were conducted to study the problem of welding discontinuous ribs to a solid base component. It was found that these welds could be achieved both when "stopping" and when "starting" the weld through control of the shape of adjacent mild-steel tooling.

In the third phase, the technical problems associated with welding to a longitudinally curved surface were examined. This work, which represents the first documented study of changed-direction welding, revealed that the considerable areas of poor welding which result when curved plates are welded using a uniform interface gap could be eliminated through control of the process parameters. Two methods were developed which produced completely welded curved plates. The first of these required that nonuniform spacing be used between the components, with the gap size adjusted as a function of the plate curvature. The second method involved confining the explosive charge in the area of maximum curvature.

Several rib-to-shell welding experiments were attempted in the nozzle configuration. The nonuniform spacing method was used in these experiments and resulted in only marginal success. The poor results attained were directly traceable to secondary effects, such as the poorly confined rib-tooling arrangement used.

This program has solved the major technical problem associated with explosive welding of complex-curved nozzles – that of welding to a longitudinally curved surface. However, practical problems, such as rib-tooling lay-up, and secondary effects in the system prevented the successful fabrication of channeled nozzle segments.

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INTRODUCTION

Present regeneratively cooled rocket-thrust-chamber designs are based mainly upon the assembly of a bundle of completely contoured tubes brazed together and joined at each end to a common manifold to provide for the circulation of the engine's fuel through the tubes as a coolant. The present fabrication technique, while in itself being very costly and difficult to perform, imposes many restrictions on the fabrication of these thrust chambers, such as materials selection and combinations, alteration of engine design, and size of engines that can be fabricated. It is therefore important that new techniques be identified and developed that will allow greater freedom in the design and fabrication of high-integrity thrust chambers at a reasonable cost.

Three characteristics of the explosive-welding process make it attractive as a possible technique for fabricating the thrust chambers. The mechanism by which explosive welds are achieved makes this process suitable for welding dissimilar materials in thin sections which are not weldable by more conventional techniques that result in melting or alloying of the materials. This should offer the potential of fabricating thrust chambers with stronger and more reliable welds and permit the design of more efficient engines. A second favorable characteristic is the small outlay of support equipment required for this fabrication process. It is possible that this would contribute to lower fabrication costs and render the process more amenable to future design changes. Lastly, the explosive-welding process is not so limited by the size of components to be fabricated, and larger size rocket engines should present no particular problem in this regard. While these characteristics of explosive welding make it a potentially suitable fabrication technique, its applicability to the complex thrust-chamber configurations must be demonstrated.

Explosive welding is a process which has been used as a method for joining both similar and dissimilar metal components over large areas. In this process, one of the components to be welded (the cladder or flyer) is accelerated to a high velocity by a detonating high explosive. This high-velocity flyer plate then impacts or collides with a second stationary component (the base plate). The collision is characterized by the velocity of the flyer plate, the angle of the collision, and the velocity at which the collision proceeds along the interface. These acceleration and collision phenomena are illustrated in Figure 1, which shows a flash X-ray shadowgraph of flat plates being explosively welded. When the above collision conditions are properly controlled, the

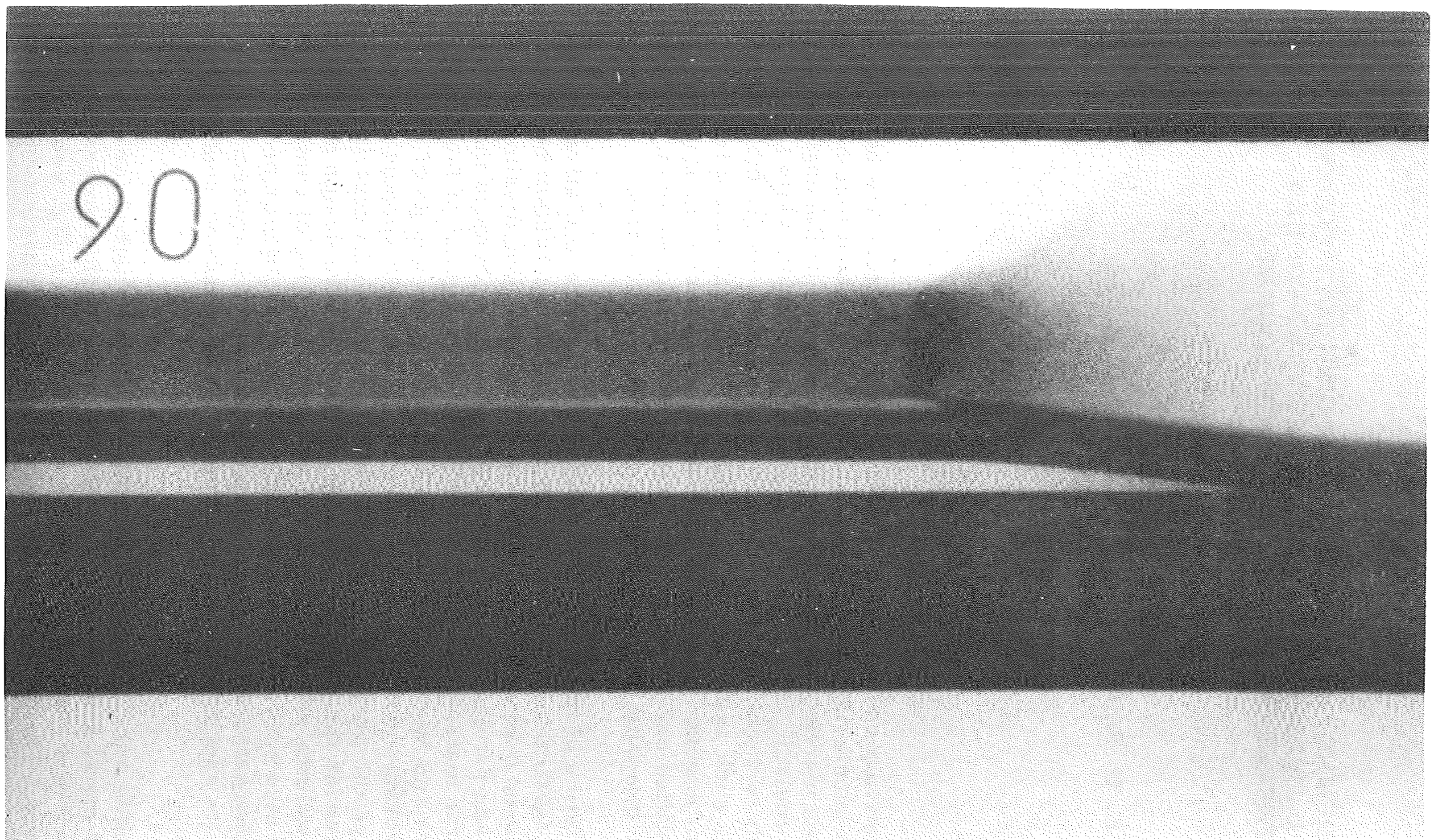


FIGURE 1. FLASH X-RAY SHADOWGRAPH SHOWING THE WELDING OF FLAT PLATES

The buffer and flyer plate are accelerated and bent through an angle by the detonating explosive charge. After traveling some distance, the flyer plate collides with the base plate at some velocity and included angle.

surface layers of each component become fluid in the region of the collision point. This high-velocity stream of material, known as a jet, is a mixture or alloy of the surface layers of the two metals, their oxide coatings, adsorbed gases, and any other contaminants present. Because of geometric and hydrodynamic considerations, the majority of the jet is expelled from the collision zone, leaving behind "clean" metal surfaces in intimate contact which metallurgically bond or weld.

This development program is therefore designed to demonstrate the feasibility of fabricating regeneratively cooled thrust chambers for large rocket engines by the explosive-welding process. It was divided into three tasks leading to an orderly development of the process. Task I was concerned with establishing the feasibility of and techniques for fabricating flat-panel sections of relatively simple design, as shown in Figure 2a, from several combinations of materials. Tasks II and III were concerned with developing techniques for fabricating spoolpieces, Figure 2b, and chamber segments, Figure 2c, respectively, of more complex but realistic configurations.

A comprehensive description of the program is presented in the sections which follow.

PROGRAM OBJECTIVE

The overall objective of the program was to develop and evaluate the explosive-welding process for fabrication of regeneratively cooled thrust chambers for large-rocket-engine requirements.

PROGRAM APPROACH

To achieve the overall objective, the program was divided into three tasks leading to an orderly development of the explosive-welding process. These tasks required the fabrication of:

Task I. Flat-Panel Specimens

Task II. Cylindrical Spoolpieces

Task III. Chamber or Nozzle Segments.

Two approaches to fabricating the channel structures were planned in the program:

(1) Liner-Welding Approach. In this approach the rib-shell structure with the channels would be machined as an integral unit from plate stock. The channels would then be filled with the desired support tooling and the liner explosively welded to the ribs. This approach would therefore involve a single explosive-welding operation. It was planned that this approach would be used to fabricate structures in all three tasks.

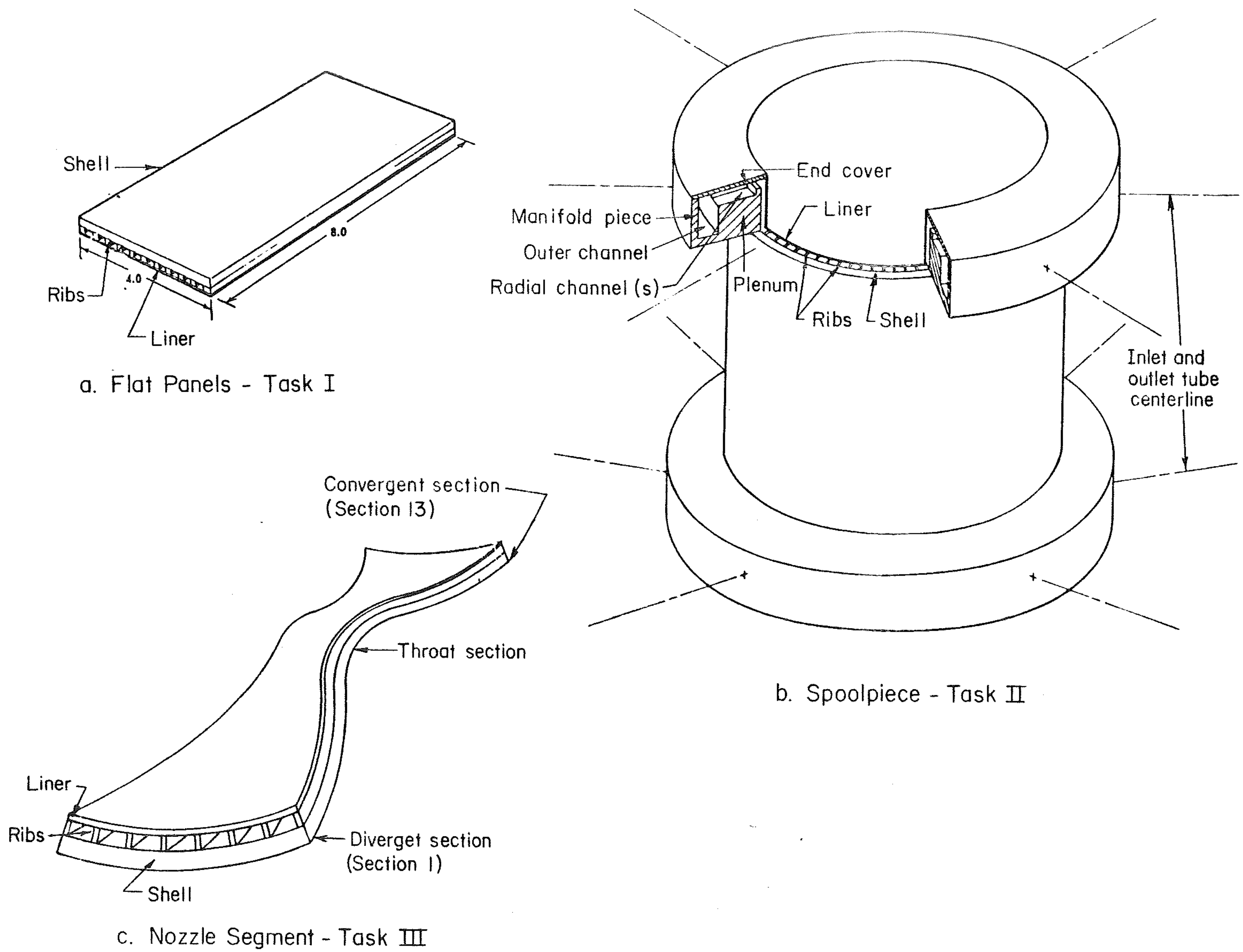


FIGURE 2. TYPES OF STRUCTURES FABRICATED IN PROGRAM

(2) Rib- and Liner-Welding Approach. This approach would involve two explosive-welding steps or operations to fabricate the structures. The first step would involve explosively welding the ribs (with appropriate tooling) to the shell component, and the second step would involve explosively welding the liner to the ribs, the same as in the first approach. It was planned that this approach would be used to fabricate flat-panel specimens and one cylindrical spoolpiece in Tasks I and II, respectively, but not for fabricating the nozzle segments in Task III.

During the course of Task I, a modified version of the rib- and liner-welding approach emerged to be a superior approach. This approach was then used to fabricate all of the full-size panels in Task I. Prior to the initiation of Tasks II and III, this approach was also selected for fabricating both cylindrical spoolpieces in Task II and the thrust-chamber segments in Task III in place of the previously planned approaches. It was anticipated that this would not cause any difficulites in the fabrication of the cylindrical spoolpieces. It did, however, have advantages and disadvantages in comparison with the previously planned approach of just explosively welding the liner to an integral rib-shell unit in the thrust-chamber segment. The newly selected approach would eliminate the costly operation of machining the variable, complex cooling channels or passages into the shell structure. The major potential problem foreseen in using the rib- and liner-welding approach was that of explosively welding the ribs to the shell component over the complex curved surface of the thrust-chamber segment. It was anticipated that the thin liner could be welded to the ribs over the curvature without too much difficulty; however, with the ribs (and mating support tooling) which was considerably thicker than the liner, it would be difficult to maintain the required constant collision conditions over the complex curved surface when welding the ribs to the shell. The economical advantages of using this approach in fabricating regeneratively cooled thrust chambers by the explosive-welding process, however, warranted the investigation of the program.

The Task I studies initially involved preliminary flat-plate experiments designed to establish the explosive-welding parameters for achieving high integrity welds between the six material combinations of interest and to characterize the resulting welds. The use of oxide coatings was also evaluated in these studies. Using these parameters, experiments were then conducted to develop the techniques and tooling concepts for the explosive welding of panel structures. First, techniques were developed for accomplishing the rib-to-shell and liner-to-rib welding operations. This technology was then applied to the fabrication of full-size panel specimens which were ultrasonically tested and hydrostatically pressurized for evaluating the integrity of their rib-to-shell and liner-to-rib welds.

In the Task II studies, the optimum results achieved in Task I were applied in the fabrication of two cylindrical spoolpieces. The initial studies in Task II involved modifying and applying the results of Task I to the three major explosive-welding operations that would be required to fabricate the cylindrical spoolpieces – rib-to-shell, end cover-to-plenum, and liner-to-rib and end-cover welds. The end cover-to-plenum welds were made necessary by a change in design of the spoolpiece at the initiation of Task II which would reduce the difficulty of machining the manifold structure in the plenum sections. The technology developed in the preliminary studies was then applied in the fabrication of two prototype spoolpieces. Following their fabrication, the completed spoolpieces were to be leak checked and hydrostatically tested prior to shipment to NASA-Lewis Research Center for actual hot testing.

The studies in Task III were divided into three phases. The initial studies, which were a major portion of the work, were directed toward the fabrication of the complex components for the thrust-chamber welding studies in the phases section of the task. The second phase was directed toward adjusting and modifying the previously developed parameters and techniques for explosively welding over the complex curved surfaces of the thrust-chamber segments. The final phase then involved explosively welding actual thrust-chamber segments and evaluating them.

TASK I. FABRICATION OF FLAT PANELS

OBJECTIVE, APPROACH, AND COMPONENT DESCRIPTION

The objective of Task I was to demonstrate the feasibility of fabricating channelled flat-plate components from several combinations of high-temperature alloys using explosive-welding methods. A secondary objective was to determine the materials and/or materials combinations which would be most compatible with the welding sequence and secondary operations such as tooling removal.

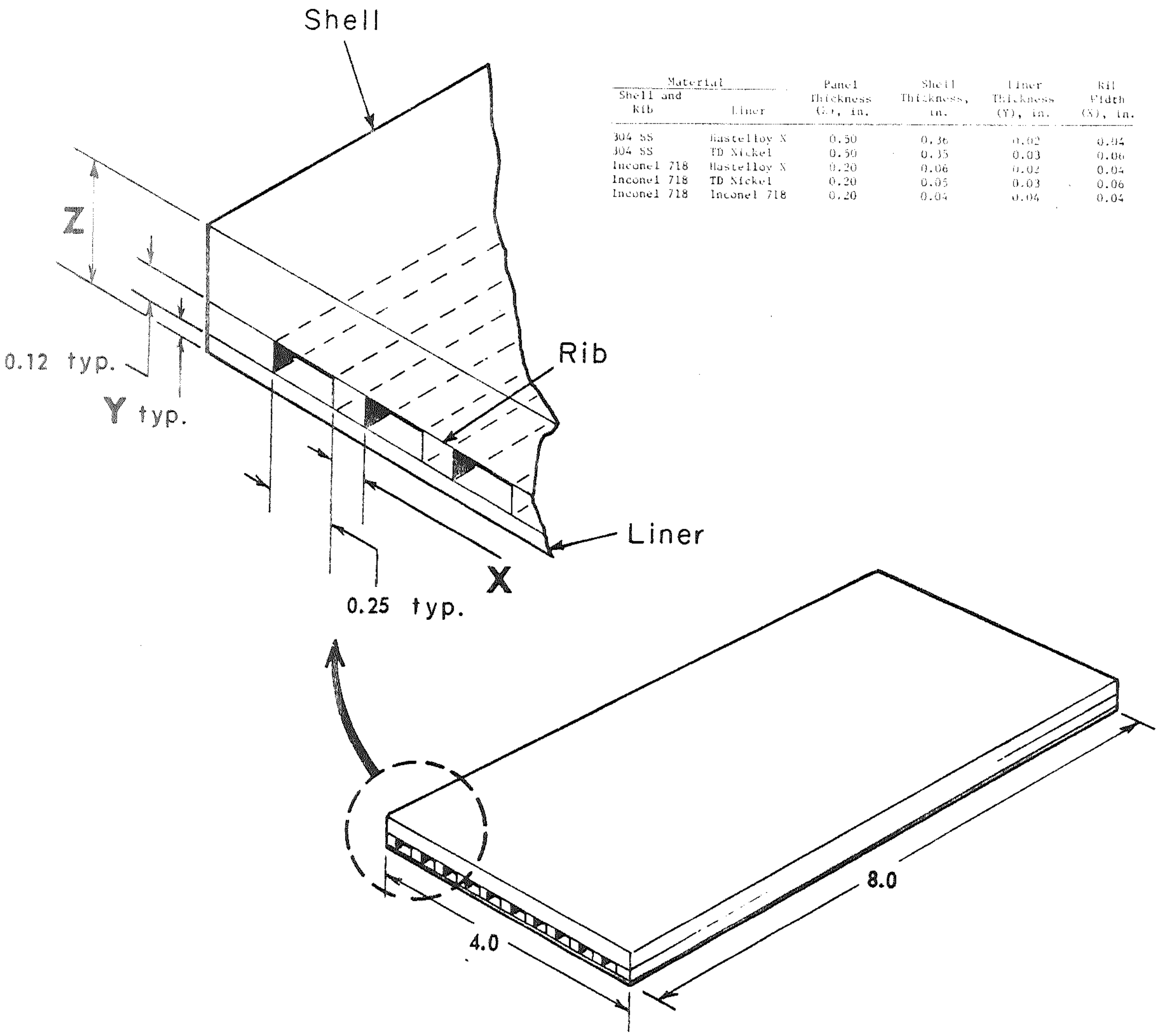
This task was performed in three phases. In the first of these, the explosive welding parameters required to produce welds between the six materials combinations of interest were developed and the properties of the welds so produced were determined. The welding parameters were developed using flat plates of the materials and thicknesses to be used in later tasks. In the second phase techniques were developed for fabricating one-or three-rib panels, and in the third phase, the best of these techniques were used to fabricate several prototype six- and nine-rib panels for evaluation.

The configuration of the required test panel is shown in Figure 3. Each panel had lateral dimensions of 4 by 8 inches, with the thickness varied according to the shell material. Each panel consisted of a shell (normally thicker than the liner), several perpendicular ribs of the same material, and a thin liner. Each of the ribs was to be completely welded to both the shell and the liner over the full length of the panel. The details of the panel construction are shown in the figure.

MATERIALS EMPLOYED

As the tabulation contained in Figure 3 shows, four materials were used in this program. Two materials – Type 304 stainless steel and Alloy 718 – were used for the shell and rib components, and three materials were evaluated for use as liners – Hastelloy X, thoria-dispersed (TD) nickel, and Alloy 718. The materials combinations and thicknesses employed in this task are presented in Table 1. These materials and thicknesses were also used in later tasks of this program in the fabrication of cylindrical (Task II) or nozzle (Task III) components.

With the exception of the Alloy 718 components, all of the materials were welded in the as-received condition (normally mill annealed). A special requirement existed for the Alloy 718 components, however. Alloy 718 increased its strength considerably upon aging, and there are several design advantages which accrue from using the material in as strong a condition as possible (this allows the thickness to be decreased and hence allows reduction in the structural weight necessary to achieve the same load-bearing capacity). Because of the potential of using the much stronger aged material, the Alloy 718 components were welded not only in the annealed condition, as were the other materials, but in the solution-treated-and-aged condition as well.



Material		Panel Thickness (Z), in.	Shell Thickness, in.	Liner Thickness (Y), in.	Rib Width (X), in.
Shell and Rib	Liner				
304 SS	Hastelloy X	0.50	0.36	0.02	0.04
304 SS	TD Nickel	0.50	0.35	0.03	0.06
Inconel 718	Hastelloy X	0.20	0.06	0.02	0.04
Inconel 718	TD Nickel	0.20	0.05	0.03	0.06
Inconel 718	Inconel 718	0.20	0.04	0.04	0.04

FIGURE 3. CONFIGURATION OF FLAT-PANEL SECTION TO BE FABRICATED IN TASK I

TABLE 1. MATERIALS AND THICKNESSES USED IN EXPLOSIVE FLAT-PANEL WELDING EXPERIMENTS

Base		Cladder		
Material	Thickness, inch	Material	Thickness, inch	Simulation of
Type 304 SS	0.375	Type 304 SS	0.125	Rib-to-shell welding
Alloy 718	0.060	Alloy 718	0.125	Rib-to-shell welding
Type 304 SS	0.060	Hastelloy X	0.020	Liner-to-rib welding
Type 304 SS	0.060	TD Nickel	0.030	Liner-to-rib welding
Alloy 718	0.060	Hastelloy X	0.020	Liner-to-rib welding
Alloy 718	0.060	TD Nickel	0.030	Liner-to-rib welding
Alloy 718	0.060	Alloy 718	0.040	Liner-to-rib welding

An additional complication was incorporated into the work with the 718 Alloy. It was found that commercial form of the alloy used in the initial experiments (Inconel 718) had quite low ductility as a result of the explosive-welding operation. The results of a recent study of this alloy* showed that a double-vacuum-melting operation would provide increased ductility in the aged condition and, in addition, would improve the response of the alloy to aging treatment. For these reasons, a commercially available double-vacuum-melted material, Allvac 718, was substituted for the Inconel 718. This substitution was made after considerable work had been done with the Inconel 718; for the sake of completeness, the work with both of these materials is reported.

The various annealing and aging treatments used for the Alloy 718 materials are presented in Table 2. This table also lists the typical yield strengths obtained from each of these treatments.

DEVELOPMENT OF EXPLOSIVE-WELDING PARAMETERS

The objective of this phase of work was to develop the parameters required to produce high-quality explosive welds between the materials combinations of interest. The materials combination for the panels required welds of the following types:

(1) Type 304 stainless steel – self-weld

(2) Alloy 718 – self-weld

(3) Type 304 stainless steel – Hastelloy X

(4) Type 304 stainless steel – TD Nickel

(5) Alloy 718 – Hastelloy X

(6) Alloy 718 – TD Nickel.

*Inouye, F. T., et al., "Application of Alloy 718 in M-1 Engine Components", NASA CR-788, June, 1967.

TABLE 2. HEAT TREATMENTS AND PROPERTIES OF ALLOY 718 MATERIALS USED IN EXPLOSIVE WELDING STUDIES

		Thermal Processing History						Representative	
		Solution Annealing		Initial Aging		Second Aging		Yield Strength	
Material	Condition	Temperature, F	Time, hr	Temperature, F	Time, hr	Temperature, F	Time, hr	0.2 percent Offset, ksi	Designation in Discussion of Experiments
Inconel	Solution annealed	1850	1	None	None	None	None	63	A
Inconel	Aged	1850	1	1350	8	1352	8	141	B
Allvac	Solution annealed	1750	1	None	None	None	None	71	C
Allvac	Solution annealed	1950	1	None	None	None	None	62	D
Allvac	Aged	1750	1	1325	8	1150	8	182	E
Allvac	Aged	1950	1	1400	10	1200	8	166	F

In this phase of the work, the weld strengths attainable between several of these combinations were determined. This work also examined the ductility of the explosive welds, and the effects of the explosive-welding operation on the microhardness of the materials.

Rectangular components, nominally 3 by 8 in., were used to determine the combination of welding parameters which produced the best welds. The materials of interest were assembled with suitable backup and support plates and welded using a commercial blasting dynamite* as the explosive charge. The parallel-plate method of welding was used in these experiments, and the complexities involved in using initially angled plates were thereby eliminated. The amount of explosive (explosive loading) and the separation (or standoff gap) between the plates to be welded were varied. Forty-two flat-plate experiments were run in this parameter-development work; they resulted in development of welding parameters which produced sound welds between each materials combination of interest.

The component arrangement used in these experiments is shown in Figure 4. As can be seen, the base plate was positioned on a thick (normally 1/2 inch) anvil plate for support. Small rectangular shims (not shown) were placed on the anvil plate, and these provided the required gap or separation between the base and cladder. As the figure shows, some of the cladder plates were attached to a steel support plate, which was then placed on the spacer shims. Other cladder plates (the 1/8-inch-thick plates used in the rib-to-shell welding simulation) did not require a support plate, and were instead placed directly on the spacer shims. A sheet of 1/8-inch-thick rubber was then placed atop the cladder or cladder support shown.

The explosive charge was loaded into a rectangular container and packed to a density of 16 g/in.^{3} (1 g/cm^3). As shown in the figure, this explosive charge was wider than both the cladder and base plates, and thereby accelerated the cladder plate to a uniform velocity over its full area. The figure also shows that the initiating end of the charge overlapped the front end of the plate assembly. This extension of the charge was used to insure that the detonation velocity of the explosive had stabilized by the time it reached the front edge of the cladder plate.

*Trojan SWP-1 – a nonnitroglycerin, nitrostarch-sensitized explosive manufactured by The Trojan Powder Company.

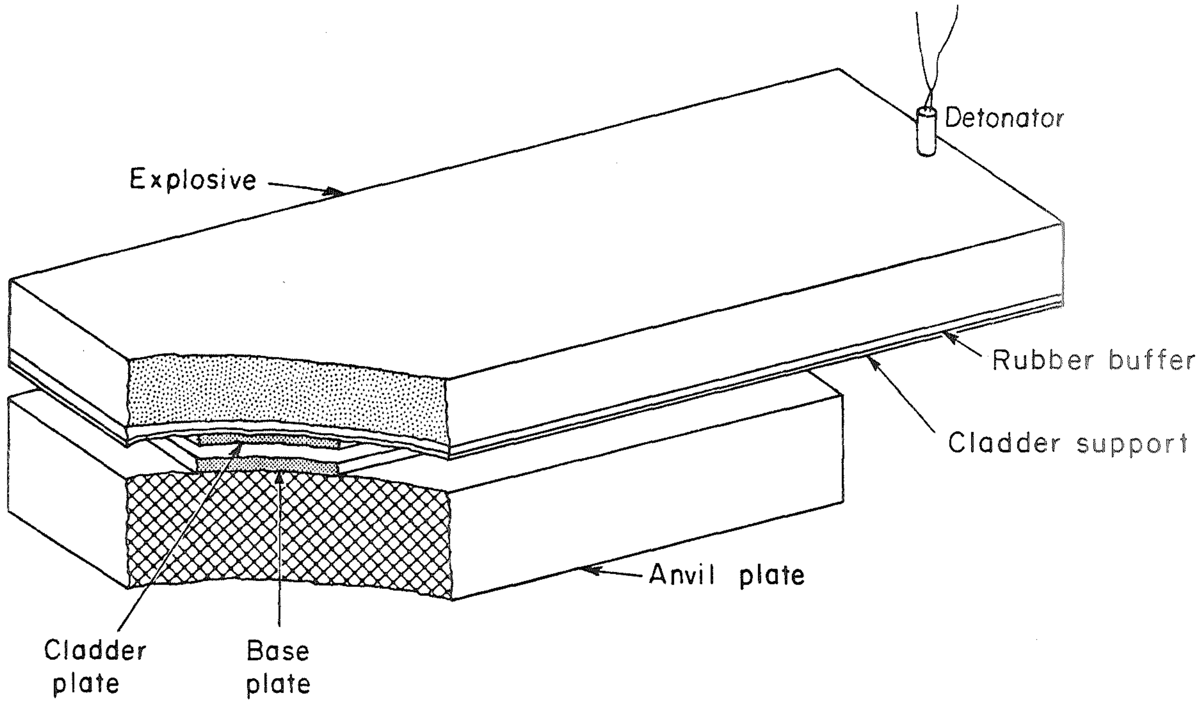


FIGURE 4. COMPONENT ARRANGEMENT USED FOR PRELIMINARY WELDING EXPERIMENTS

The initial set of welding parameters used for each of the materials combinations was chosen on the basis of past explosive-welding experience. The plates welded with parameters were sectioned, and the quality of the welds produced was determined by means of chisel-peel testing and, when required, by metallographic examination. The ease with which the welded plates, could be separated, together with the appearance of the weld interface, was used as a basis for a preliminary assessment of the quality of the weld.

The welding parameters were then modified on the basis of these results. It was found that in most cases the original parameters were "low", and it was necessary to either increase the explosive loading and/or increase the standoff gap to achieve good welding. This iteration process of welding, preliminary evaluation, and parameter adjustment was continued until sound welds were produced for each of the materials combinations.

The parameters found to produce the best welds in each of the combinations of interest are listed in Table 3. It will be noted that Alloy 718 in the aged condition required "higher" welding parameters than it did in the annealed condition. In fact, the explosive loading required to weld aged Alloy 718 to itself was so much higher than the loading needed for the annealed material that it was decided it would be impractical to self-weld the aged material in a panel configuration. An analysis of the load-bearing requirements of the structures showed that the higher strength achieved by aging would be needed only in the shell component; consequently, only the shell was aged, and the ribs and liners were used in the annealed condition. All later experiments with Alloy 718 were performed using this combination of heat-treated materials.

Detailed Evaluation of Welded Flat-Plate Components

The routine examination given to all of the explosively welded coupons was extended to characterize more fully those welds which were produced with the best parameters – those given in Table 3. This examination included metallographic examination and photomicrographic documentation, tensile-shear tests of the weld strength, determination of microhardness profiles of the welded plates, and evaluation of the weld ductility by means of bend testing.

The welds produced using the parameters listed were sound and contained little or no trapped jet and melt. All of these welds exhibited the rippled interface characteristic of good welds. Figures 5 and 6 show welds produced between the materials systems of interest.

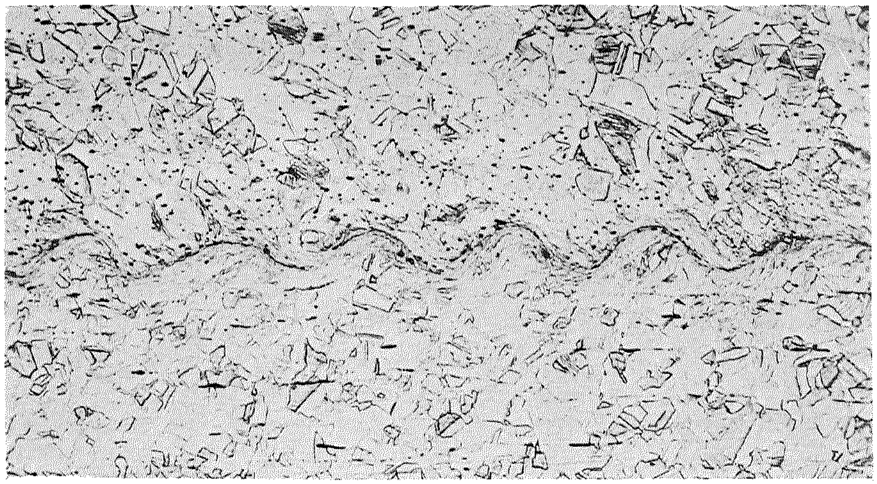
TABLE 3. SUMMARY OF BEST EXPLOSIVE-WELDING PARAMETERS AS DETERMINED FROM FLAT-PLATE WELDING EXPERIMENTS

Material Combination						Explosive-Welding Parameters	
Base Plate		Cladder					
Material	Heat Treatment[(a)]	Material	Heat Treatment	Nominal Thickness, in.	Cladder Support Thickness, in.	Standoff Gap, in.	Explosive Thickness, in.
Type 304 SS	--	Type 304 SS	--	0.125	--	0.060	11/16
Type 304 SS	--	Hastelloy X	--	0.020	1/16	0.050	9/16
Type 304 SS	--	TD Nickel	--	0.030	1/16	0.060	9/16
Inconel 718	A	Inconel 718	A	0.125	--	0.100	9/16
Inconel 718	B	Inconel 718	B	0.125	0.019	0.100	1-5/16
Allvac 718	C	Allvac 718	C	0.060	0.019	0.094	9/16
Allvac 718	F	Allvac 718	F	0.060	0.019	0.050	1-11/16
Inconel 718	A	Hastelloy X	--	0.020	1/16	0.050	9/16
Inconel 718	B	Hastelloy X	--	0.020	1/16	0.070	11/16
Inconel 718	A	TD Nickel	--	0.030	1/16	0.060	9/16
Inconel 718	B	TD Nickel	--	0.030	1/16	0.060	11/16

(a) As specified in Table 2.

Determination of the Weld Strength

The quality of the welds produced using the "best" parameters was determined by examining the strength of the welds. This evaluation was performed using a tensile-shear test in which the weld between the components is tested in a shear mode. The configuration used in this test is shown in Figure 7. This test has proven useful as a measure of weld strength, even though the bending moment which exists in the test zone may be significant for materials of unequal thickness.



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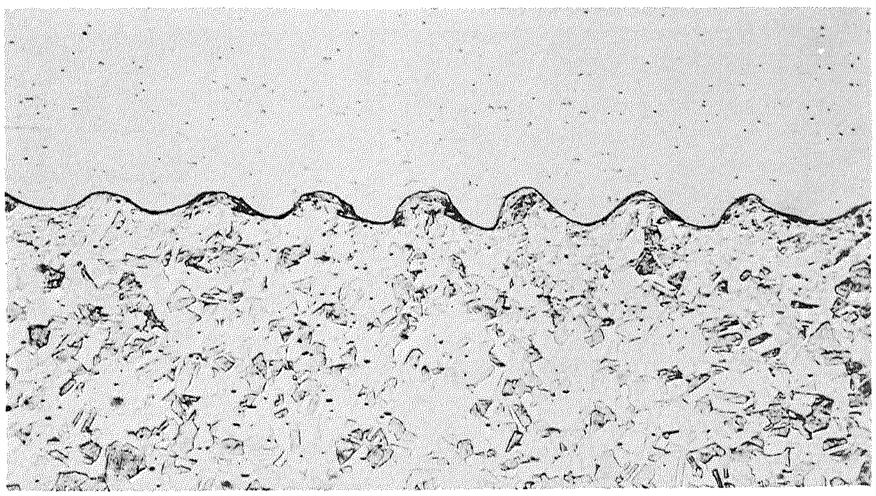
a. Type 304 SS Welded to Itself



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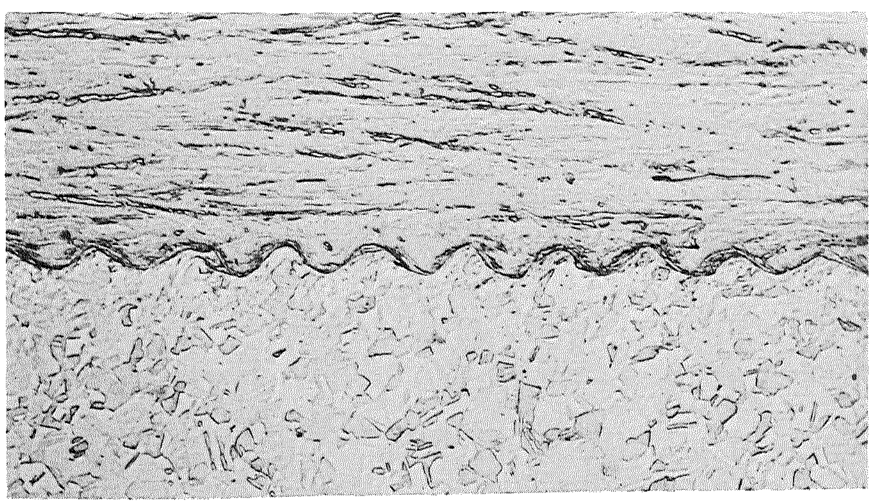
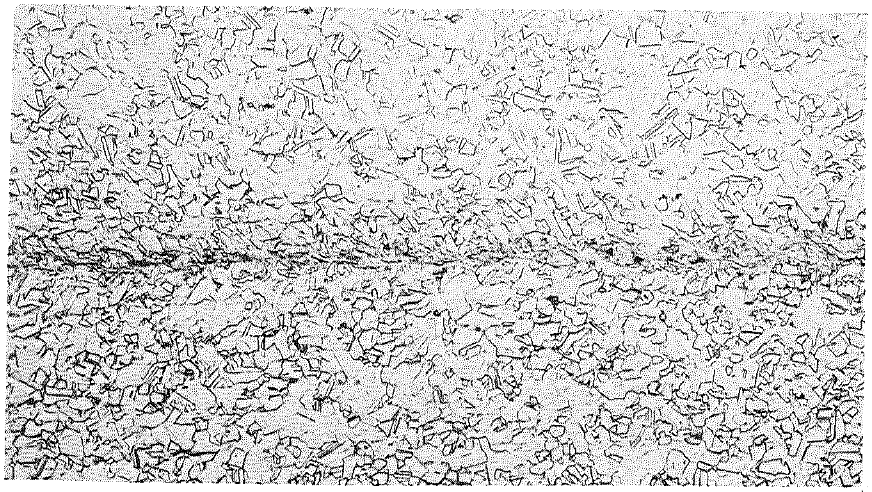
b. Weld Interface Between Type 304 SS and Hastelloy X



100X 4C158

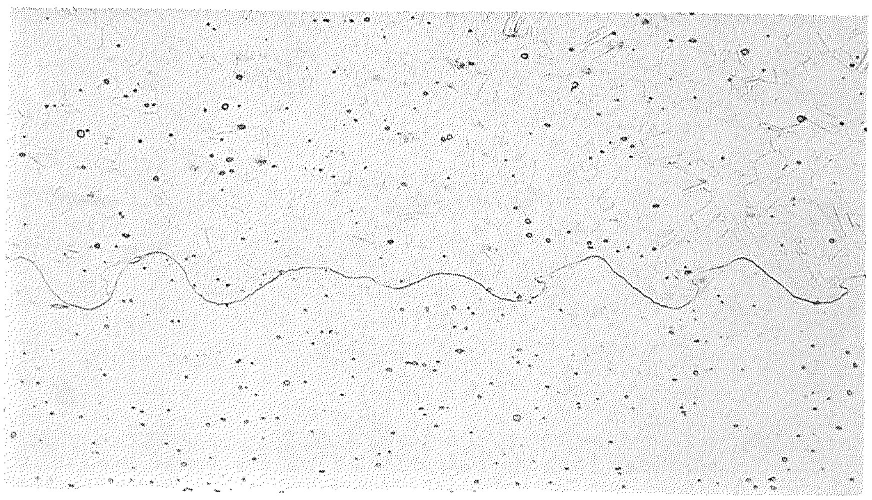
c. Weld Interface Between Type 304 SS and TD Nickel

FIGURE 5. EXPLOSIVE WELDS PRODUCED WITH TYPE 304 STAINLESS STEEL USING THE OPTIMUM WELDING PARAMETERS



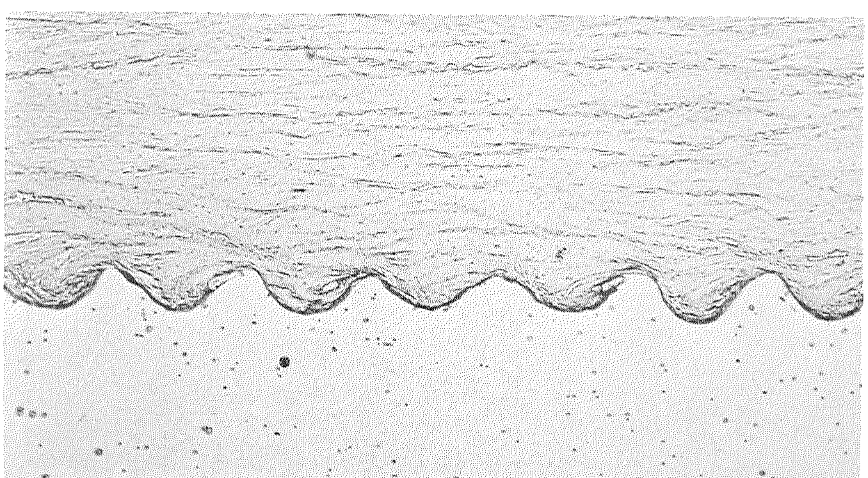
100X 5C342

a. Allvac 718 Welded to Itself



100X 3C395

b. Weld Interface Between Allvac 718 and Hastelloy X



100X 3C391

c. Weld Interface Between Allvac 718 and TD Nickel

FIGURE 6. EXPLOSIVE WELDS PRODUCED WITH ANNEALED ALLVAC 718 USING THE OPTIMUM WELDING PARAMETERS

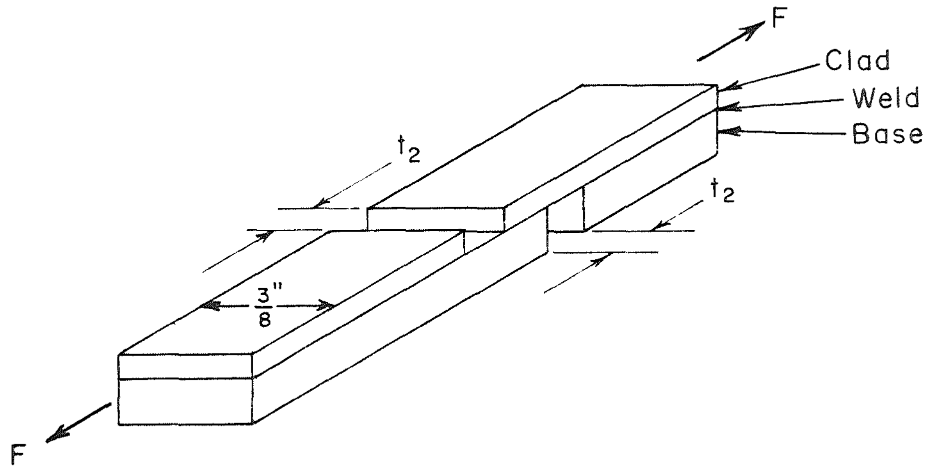


FIGURE 7. TENSILE-SHEAR SPECIMEN USED TO MEASURE STRENGTH OF EXPLOSIVE WELDS

Clad = t

Base = t_2; $t_2 \geq t$.

Duplicate specimens of several combinations of most interest were machined from the welded flat plates and tested at 0.02 ipm until failure. To provide a direct comparison between the explosively welded plates and the inherent strength of the base metals, several test specimens were machined from solid plates of both Type 304 SS and annealed Alloy 718 and tested in duplicate.

The data obtained in the tensile-shear tests are presented in Table 4. The measured strength levels were in all cases at least as high as, and in several cases higher than, the static yield strengths of the parent metals. The data also show that the self-welds produced between Type 304 SS were stronger than the solid material. This result is attributed to the considerable work hardening of the interface which occurred during welding.

Measurements of Work Hardening Caused by the Welding Operation

The extent of material strengthening and work hardening induced by the explosive-welding operation was determined through use of microhardness measurements. Knoop microhardness measurements using a 500-gram load were taken on samples of each material before explosive welding, and were also taken on polished cross sections of representative welded coupons. Measurements were taken at 0.001-inch intervals for a distance of 0.005 inch from each surface (both the welded interface and each external surface) and then at 0.005-inch intervals for distance of 0.060 inch from each surface. Three indentations were made at each lateral position and the results averaged to give a value for each distance. The results of these measurements indicated that most of the materials were hardened considerably by the explosive-welding operation, and that most of the hardness increase (due to shock hardening) was confined to about 0.030 inch on either side of the welded interface. Except for the thinner TD Nickel and Hastelloy X cladder materials, which hardened through their entire thicknesses, no significant hardness increase was noted at the external surface of any of the other materials.

TABLE 4. RESULTS OF TENSILE-SHEAR TESTS OF EXPLOSIVELY WELDED COUPONS

Material Component: Base Component	Material Component: Cladder Component	Maximum Load, lb	Weld Area, in^2	Shear Strength, psi	Remarks
304 SS	304 SS	2050	0.0233	89,000	Broke at weld
304 SS	304 SS	2120	0.0233	91,000	Broke at weld
304 SS Control		1900	0.0250	75,700	Broke in shear area
304 SS Control		1660	0.0250	66,300	Broke in shear area
304 SS	TD Nickel	1005	0.0133	89,600	Broke at weld
304 SS	TD Nickel	980	0.0133	87,200	Broke in TD Nickel
304 SS	Hastelloy X	802	0.0075	107,000	Broke at weld
304 SS	Hastelloy X	815	0.0075	109,000	Broke at weld
Inconel 718[(a)]	TD Nickel	996	0.0113	88,500	Broke in TD Nickel
Inconel 718[(a)]	TD Nickel	866	0.0113	77,000	Broke at weld
Inconel 718[(a)]	Hastelloy X	840	0.0075	112,000	Broke at weld
Inconel 718[(a)]	Hastelloy X	870	0.0075	116,000	Broke at weld
Inconel 718 Control		1522	0.0157	96,700	Broke in base material
Inconel 718 Control		1385	0.0157	88,000	Broke in shear area

(a) Aged according to Heat-Treatment B; yield strength 141 ksi.

Typical microhardness surveys are shown in Figure 8 for all of the materials of interest. The values obtained represent the values obtained with similar welding parameters. While other conditions of explosive loading or standoff (which influenced the collision velocity) exhibited slightly different values, the same relative hardening was achieved.

It can be seen that the largest hardness gradient and greatest change in hardness from the original material (given in parentheses) were produced in Hastelloy X, Type 304 SS, and annealed Inconel 718. A somewhat less but significant hardness change was also produced in the aged Inconel 718. The smallest hardness gradient and least change were produced in the TD Nickel.

Determination of Weld Ductility

Bend tests were made to determine the ductility of both the welded interfaces and the base materials after the welding operation. For comparison, as-received and aged materials were also bend tested. Bend-test coupons were taken from welded coupons which were fabricated using the welding parameters given in Table 3. Two coupons, each 3 to 5 inches long and 0.625 inches wide, were machined from each welded plate. Each set of specimens was bent 120 degrees using a punch radius twice the specimen thickness (2T); one specimen was bent with the thinner cladder component facing up (cladder in compression), while the other was bent with the cladder component facing

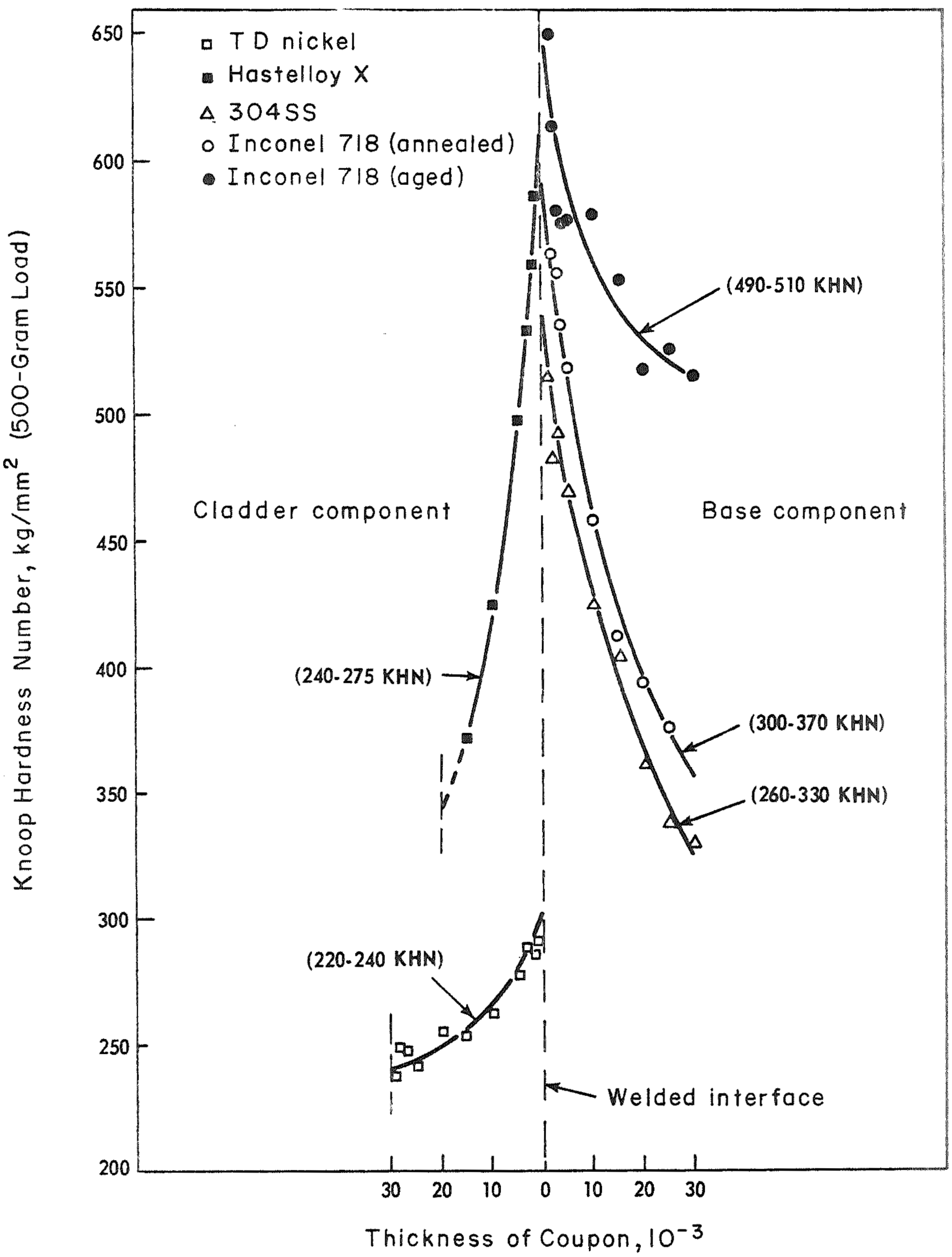


FIGURE 8. MICROHARDNESS TRAVERSES FOR EXPLOSIVELY WELDED MATERIALS

Numbers in parentheses represent as-received hardness values.

down (cladder in tension). After bending, each specimen was examined visually and in some instances metallographically, for evidence of damage.

All of the systems containing Type 304 SS cound be bent through a 120-degree, 2T radius without damage or cracking of the weld or the parent material. However, the welds produced between age-hardened Inconel 718 and either Hastelloy X or TD Nickel showed much different behavior. When these coupons were bent with the cladder plate in compression, no evidence of damage was noted, as shown in Figure 9a. However, similar coupons bent with the cladder plate in tension cound not withstand the 2T bend radius and thus fractured as shown in Figure 9a.

This behavior may be explained by considering the position of the coupon's neutral axis relative to its weld interface during bending. Because the thickness of the cladder was always less than that of the Inconel 718 base, the position of the neutral axis did not correspond to the weld interface. Therefore, when a coupon was bent with the Inconel 718 on the bottom, most of this component was in tension, but the weld itself and its work-hardened regions were in compression and no damage resulted. This situation was reversed when a coupon was bent with the Inconel 718 on top. Although most of the Inconel 718 was now in compression, the weld and its work-hardened regions, being below the neutral axis, were subjected to tension. The Inconel 718 in this region did not have sufficient ductility and cracks were initiated. Further support for this reasoning is given by the small crack visible in Figure 9b near the welded interface. Failure of the specimen shown was probably initiated from such a crack.

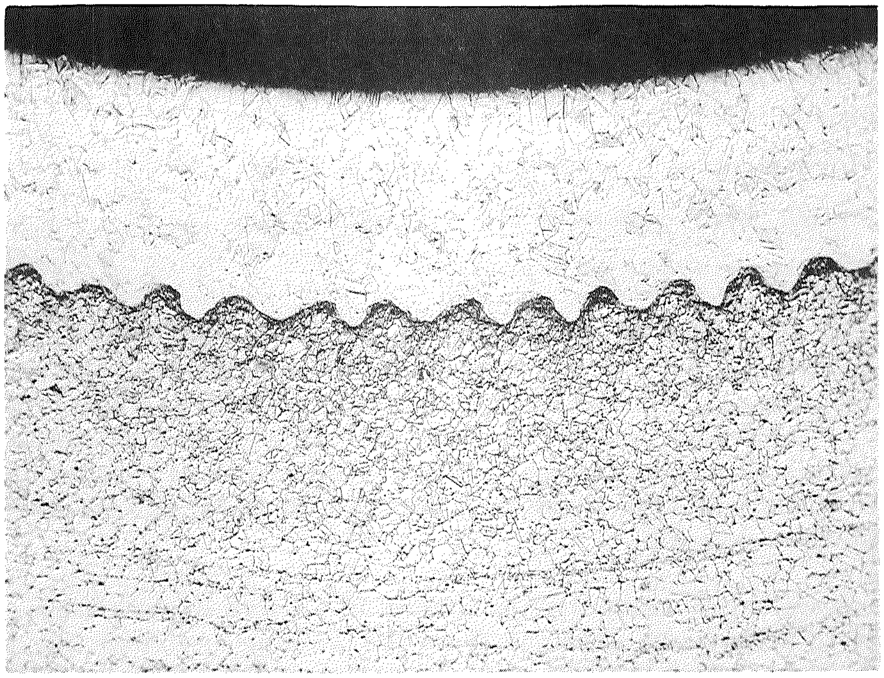
An effort was made to bend specimens from a welded coupon consisting of age-hardened Inconel 718 components of equal thickness. Although they cound be bent 120 degrees over a 1/2-inch radius (4.2T), failure resulted when they were bent 120 degrees over a 3/8-inch radius (3.1T).

For purposes of comparison, specimens of as-received, annealed, and aged materials were also bend tested. In all cases, the as-received or annealed materials cound be bent to a 1T, 120 degree bend without any visual evidence of cracking. However, none of the aged Alloy 718 materials cound be bent to less than a 2T radius without damage.

Explosive Welding of Plasma-Sprayed Components

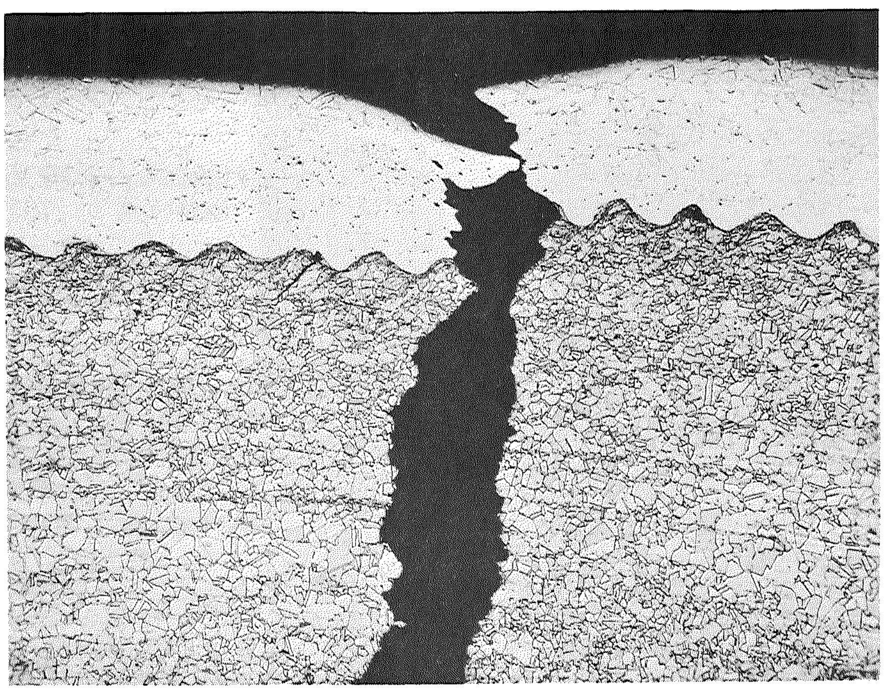
Several experiments were conducted in which Hastelloy X, plasma-sprayed on one surface, was explosively welded to 304 SS. The purpose of these experiments was to determine whether ceramic coating would remain intact throughout a liner-to-rib welding operation. A Mo-ZrO_2 coating was selected for use from several candidate coatings because it was considered most likely to survive the welding operation.

Sheets of Hastelloy X, 0.020 by 3 by 5 inches, were plasma-sprayed on one surface with either a 0.020-inch thick layer of pure ZrO_2 or a graded Mo-ZrO_2 coating. A Thin layer of molybdenum was used under the pure ZrO_2 coating to improve the coating adherence. The graded coating consisted of five layers, each 0.003 to 0.004 inch thick, having the nominal compositions indicated below:



50X 4C213

a. Hastelloy X in Compression



50X 4C211

b. Hastelloy X in Tension

FIGURE 9. BEND TESTING OF WELDS BETWEEN HASTELLOY X AND INCONEL 718

The specimens were bent 120 degrees over a 2T radius.

Substrate – Hastelloy X

First layer – 100 wt % molybdenum

Second layer – 75 wt % Mo – 25 wt % ZrO_2

Third layer – 50 wt % Mo – 50 wt % ZrO_2

Fourth layer – 25 wt % Mo – 75 wt % ZrO_2

Fifth layer – 100 wt % ZrO_2

The coated Hastelloy X and 304 SS plates were welded using the welding parameters established earlier for the Hastelloy X 304 SS system (0.05-inch standoff gap and 9/16-inch-thick explosive charge). In each experiment, the coated Hastelloy cladder plate was attached to 1/16-inch-thick sheet steel with the coated side next to the steel to attenuate the effects of the explosive charge. In some experiments, a nominal 1/8-inch-thick layer of rubber was also positioned between the steel and the explosive to further buffer the explosive effects.

As expected, the Hastelloy X welded to the 304 SS in all five experiments. However, despite the efforts to protect the coatings from the welding environment, none of them survived without damage. The pattern of damage illustrated in Figure 10 for a pure ZrO_2 coating was typical of all the coatings, whether pure or graded. The molybdenum layer adhered to Hastelloy in most areas of each specimen, while the oxide and graded oxide coating separated from the molybdenum for over half of the surface area. As shown in Figure 10, the oxide layer which did adhere was cracked severely.

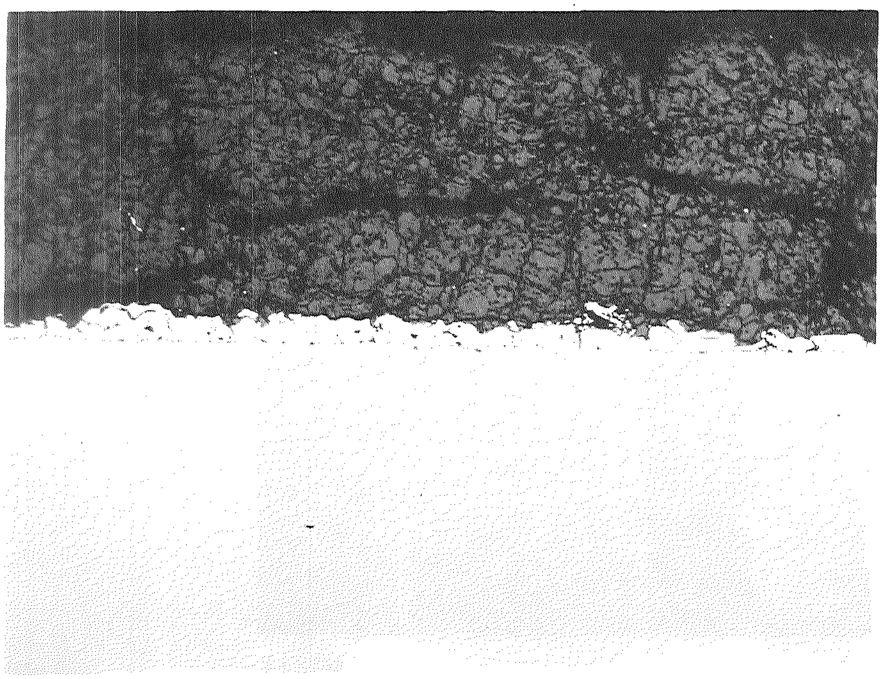


FIGURE 10. DAMAGE PRODUCED IN ZrO_2 COATING UPON EXPLOSIVELY-WELDING HASTELLOY X SUBSTRATE TO STAINLESS STEEL

The thin layer of molybdenum was put on the Hastelloy substrate to improve the adherence of the ZrO_2 coating.

These results indicate that neither pure ZrO_2 or graded Mo-ZrO_2 plasma-sprayed coatings can survive the stresses generated by explosive welding. Separation of the coatings from the molybdenum probably occurs by a spallation mechanism, either from stress reverberations within the cladder assembly during acceleration or from tensile rarefaction stresses generated during the impact of the cladder with the base. The cracks within the coatings are attributed to the bending of the cladder assembly which occurs as it is accelerated. Other experimental evidence has shown that the cladder assembly bends through an angle of between 8 to 9 degrees for the cladder-plate thickness and explosive loading used.

DEVELOPMENT OF TECHNIQUES FOR FABRICATING THREE RIB-PANEL SPECIMENS

The objective of this phase of Task I was to develop the procedures for explosively fabricating subscale specimens of the flat-panel configuration shown in Figure 3. In this work, techniques were developed for the rib-to-shell welding operation using one- and three-rib panel specimens, and the liner-to-rib welding step was studied using three-rib panels.

Rib-to-Shell Welding Experiments

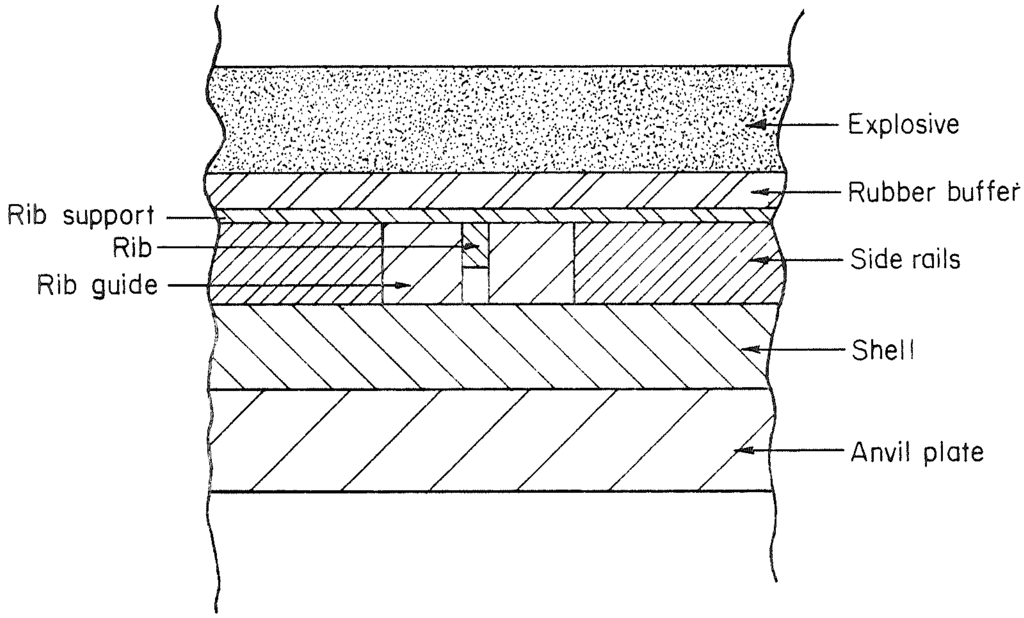
The spoolpiece configuration to be fabricated in Task II required that the rib-to-shell welding operation be conducted by accelerating the ribs against the shell, rather than by accelerating the shell against the ribs. It was also required that the ribs be confined and prevented from extruding laterally during the welding operation.

Three techniques were considered for explosively welding the ribs to the shell components. Two of these methods employed stationary tooling which was in initial contact with the shell and accelerated the ribs against the shell between these tooling pieces. In the first of these methods, a single rib was used. This method was not successful, but led to a laminated-rib technique which produced marginal welds. In the third technique, movable tooling was employed and this proved to be a practical way to produce sound rib-to-shell welds. The development of this integralrib technique was the most important milestone in Task I, as it permitted high-integrity rib-to-shell welds to be consistently produced.

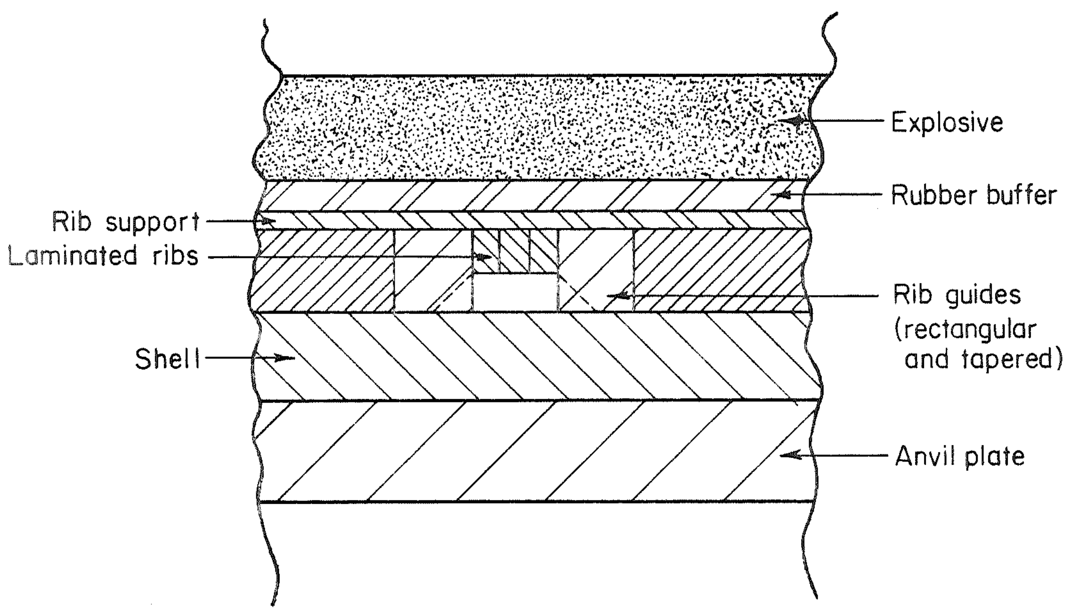
A successful rib-to-shell welding method was developed using 304 SS ribs and shells. Following this development effort, the same techniques were used to fabricate three-rib panels from Allvac 718.

Single and Laminated Rib Techniques

The various components and their arrangement for the single-rib experiments are shown in Figure 11a. A 3/8 by 2 by 8-inch 304 SS shell was supported on a 1/2-inch-thick steel backup plate, and steel rib guides, 3/16 by 1/4 by 8 inches, were positioned on the shell plate adjacent to two 3/16 by 1-inch steel rails, as shown. A single 0.062 by 0.120 by 8-inch 304 SS rib was attached with double-stick tape at a 0.019-inch-thick



a. Single-Rib Technique



b. Laminated-Rib Technique

FIGURE 11. COMPONENT ARRANGEMENTS FOR EARLY RIB-TO-SHELL WELDING EXPERIMENTS

304 SS support plate, and this rib support was positioned on the rib guides so that the attached rib fit between them. A 1/8-inch rubber buffer and the explosive charge were next positioned on the support plate. The explosive charge overlapped the experimental area, as described previously, and was detonated using an electric blasting cap.

Four experiments were conducted using this arrangement. The sizes of the rib and side components provided for a 0.060-inch standoff gap between the rib and the shell, and explosive layer thicknesses were between 11/16 and 13/16 inch. None of these experiments produced any rib-to-shell bonding whatever.

The failure of this method was attributed to two factors. One of these was the lateral expansion of the rib guides under shock loading and the consequent wedging and "pinning" of the rib before it had achieved full velocity. According to this explanation, the lateral Poisson expansion would be more severe and the rib would consequently move less for higher explosive loadings, a result which was in fact observed.

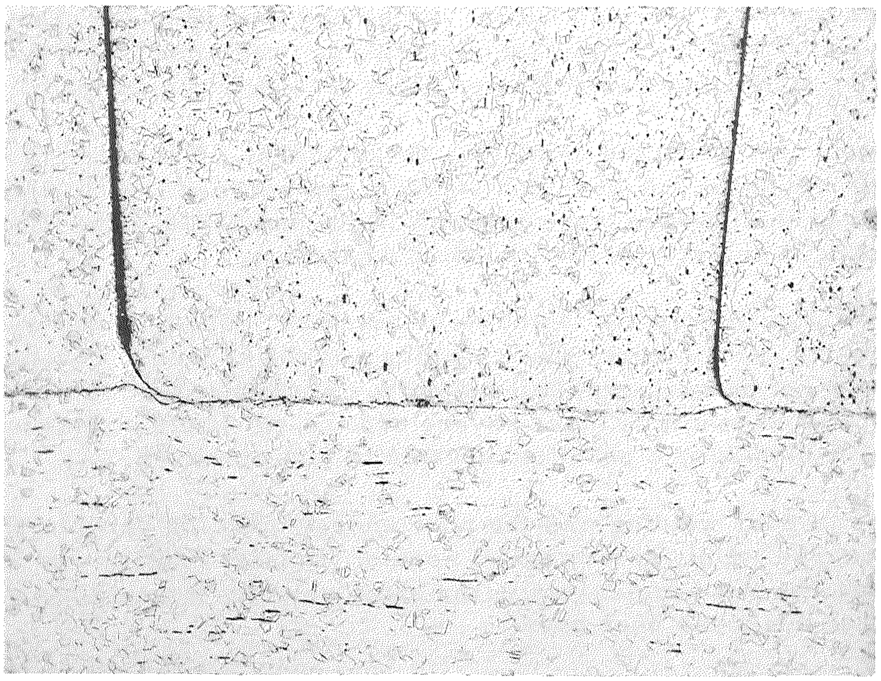
The second cause of poor welding was the poor energy coupling between the single rib and the explosive charge. Only a very small area of transfer contact was available and consequently the rib was not accelerated to the same velocity it would have reached had a solid plate of equal thickness been used.

A modification of this stationary-tooling approach was used in an attempt to overcome the two hindering factors. The stainless steel rib to be bonded was laminated between two equally sized ribs of mild or stainless steel, and this composite rib was positioned between the rib guides as before. The assembly used in these experiments is shown in Figure 11b. Some of these laminated rib experiments used solid rib guides, as were used in the single-rib experiments, while others used rib guides which were chamfered (indicated by dashed lines in Figure 11b. The remainder of each assembly and the welding parameters used were identical to those used in the single-rib experiments.

Twelve experiments were conducted using the laminated-rib technique. Explosive-charge thicknesses of between 11/16 and 1 inch were used in these experiments. The support ribs were removed after welding, either by acid leaching (50-50 nitric acid-water solution at 200 F) or by mechanical means, which was possible since they were not themselves welded to the shell. Metallography and mechanical peel tests were used to evaluate the weld between the central rib and the shell.

It was found that some degree of rib-to-shell welding was produced using the laminated-rib technique. The use of mild-steel support ribs resulted in lateral extrusion of the mild steel between the stainless steel rib and the shell which produced a poor weld. The use of stainless steel for the support ribs resulted in better welds, although welding was not achieved over the full length of the sample. A typical welded interface produced using this material combination is shown in Figure 12.

At this stage of the program, it became apparent that high-integrity rib-to-shell welds could not be reliably produced by accelerating only the rib components while the support tooling remained in contact with the shell. When explosive-charge levels were sufficiently high to accelerate the 304 SS rib components, extensive lateral extrusion of the support tooling prevented the ribs from contacting and welding to the shell in most areas. The use of high-strength tooling and tapered tooling designs did not improve the situation to any extent. Therefore, the laminated-rib technique was abandoned.



304 SS ribs

304 SS shell

50X 5C109

a. Transverse Section

304 SS rib

304 SS shell

100X 5C107

b. Longitudinal Section

FIGURE 12. RIB-TO-SHELL WELDS PRODUCED USING THE LAMINATED-RIB TECHNIQUE

Integral-Rib Technique

A new approach was used to overcome the problems encountered in the one- and three-rib welding experiments discussed above. In this new method, both the ribs and the tooling components were accelerated across an interfacial gap. The component arrangement used to weld a three-rib panel is shown in Figure 13. The ribs and spacer tooling were interspersed as shown and held to the support plate and in close lateral contact with double-sided tape. The stainless steel ribs were slightly higher than the mild-steel tooling, and produced a "step" effect of 0.005 inch as shown. This step was used to insure that the rib contacted the shell before the tooling did, thereby preventing the tooling from contaminating the rib-to-shell weld. The remainder of the experimental assembly was similar to that used previously.

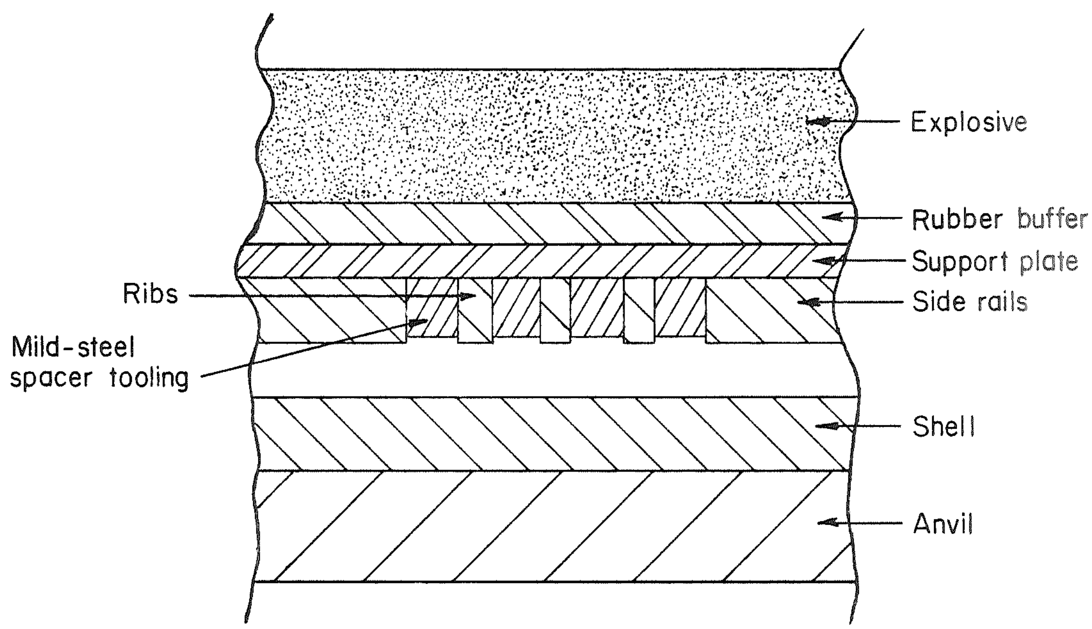


FIGURE 13. INTEGRAL-RIB METHOD FOR RIB-TO-SHELL WELDING

This technique produced sound welds, as the motion of the ribs was not hindered by the tooling.

A series of experiments was run to evaluate the performance of this rib-tooling concept. This evaluation was performed using the stainless steel system, and when it was found that high-quality welds cound be produced, the method was used to fabricate the Alloy 718 components.

The stainless steel specimens were welded using parameters developed in the preliminary flat-plate welding studies – a 0.068-inch standoff distance and explosive-charge thicknesses of 11/16 and 3/4 inch. After welding, the steel tooling was removed from the specimens by acid leaching (using hot, 50 percent nitric acid) and metallographic samples were cut showing transverse and longitudinal sections of the rib-to-shell weld interfaces. Examination of these samples revealed that rib-to-shell welding was achieved with both of these explosive loadings, but the panels welded using the higher load exhibited stronger welds. The appearance of a typical rib-to-shell weld produced using a 3/4-inch-thick charge is shown in Figure 14.

Allvac 718 specimens were welded using a similar configuration. A 0.100-inch standoff distance and explosive-charge thicknesses of 9/16 to 3/4 Inch were used in these experiments. In these experiments, shell components in the aged condition and ribs in the solution-annealed condition were employed. The decision to use this combination of heat-treatment condition was made during the flat-plate welding work, and resulted from the difficulty experienced in welding age-hardened Alloy 718 to itself. Because this combination of aged and annealed materials had not been previously welded, a range of explosive loadings were used so that the welding behavior of this system could be examined.

The panels were evaluated metallographically in the same manner as the stainless steel panels. The quality of the welds increased as the explosive loading increased, with the panels welded using 3/4-inch-thick charges showing very strong welds.

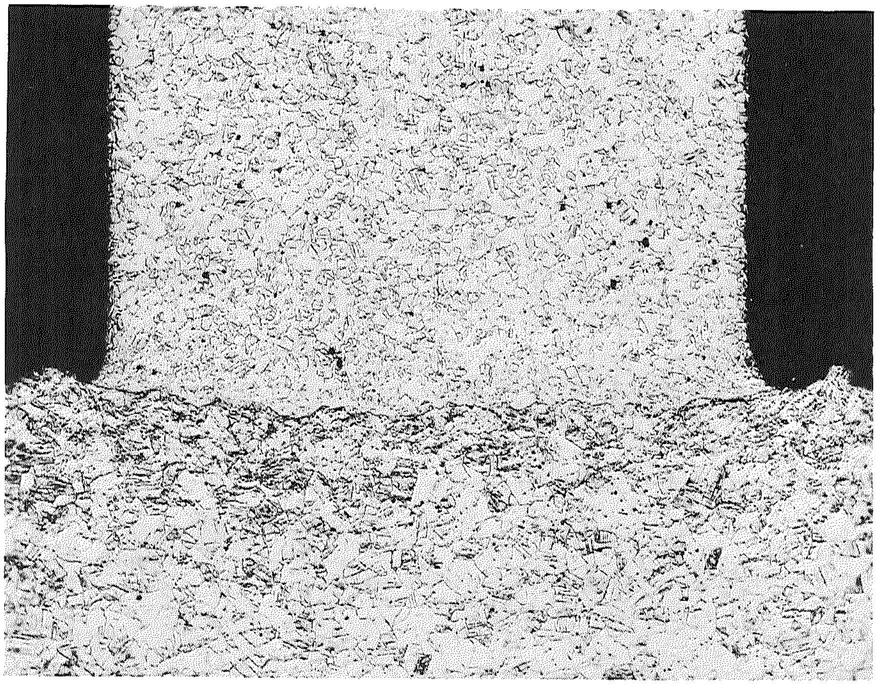
It was found that for both of these materials systems, the explosive loadings required to achieve strong rib-to-shell welds were greater than those used in the flat-plate experiments. The welds produced with these modified parameters were strong and sound, and extended over the full area of the rib-shell contact area.

Liner-to-Rib Welding Experiments

The liner-to-rib welding operation was the second major step in explosively welding flat-panel sections. This weld was made by welding the liner directly to the shell-rib structure which had been fabricated by the integral-rib technique and this welding operation would be the same for both approaches that were to be used in later tasks. An important benefit derived from the integral-rib technique in rib-to-shell welding was that the spacer tooling required in the liner-welding operation was in place as a result of the rib-to-shell welding operation and could be used without further modification.

Several three-rib stainless steel and Allvac 718 rib-shell structures were fabricated using the integral rib-welding technique. These structures were then prepared for the liner-to-rib welding operation by flattening them and then reducing the height of the tooling so that the ribs extended several mils above the tooling. Hot nitric acid was applied by hand to reduce the tooling heights. Figure 15 illustrates the arrangement of components used in a typical liner-to-rib welding experiment. The assembly and welding procedures used in these experiments were the same as those used in the preliminary flat-plate welding experiments.

Hastelloy X liners were welded to both stainless steel and Allvac 718 rib-shell structures using standoff distances of 0.050 inch and 0.070 inch, respectively. Explosive-charge thicknesses of 9/16 inch were used for the 304 SS structures, charge thicknesses of 5/8 and 11/16 in. were used for the Allvac 718 structures. The tooling was leached from each of the panels after welding, and samples were cut from each which showed transverse and longitudinal sections of the weld between the liner and the middle rib. Other samples of the panels were subjected to peel tests. The welds between Hastelly X and both stainless steel and annealed Allvac 718 were examined metallographically and showed the continuously rippled interfaces characteristic of good welding.

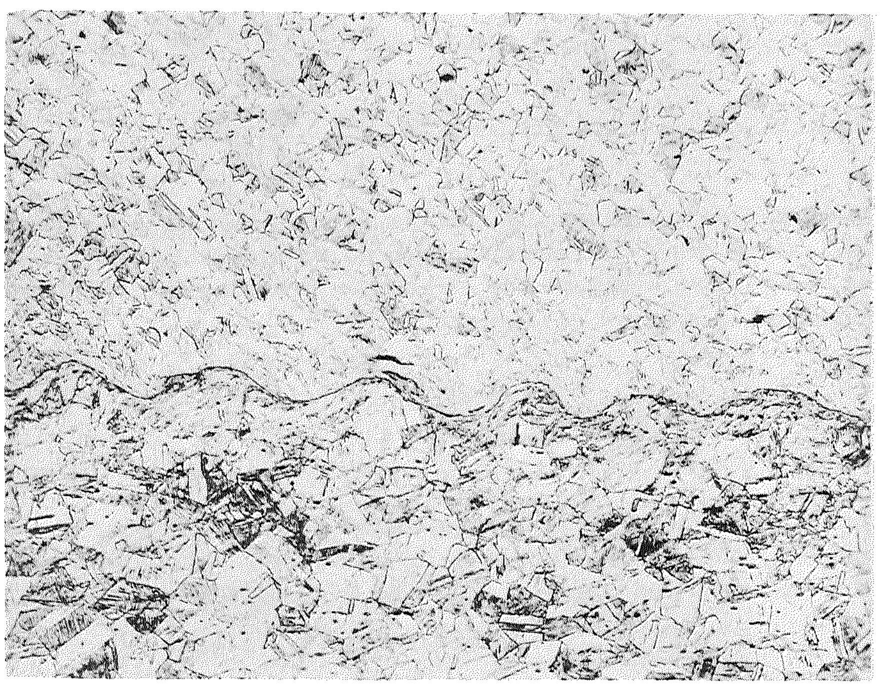


304 SS rib

304 SS shell

50X 5C563

a. Transverse Section



304 SS rib

304 SS shell

100X 5C562

b. Longitudinal Section

FIGURE 14. RIB-TO-SHELL WELD PRODUCED USING THE INTEGRAL-RIB METHOD

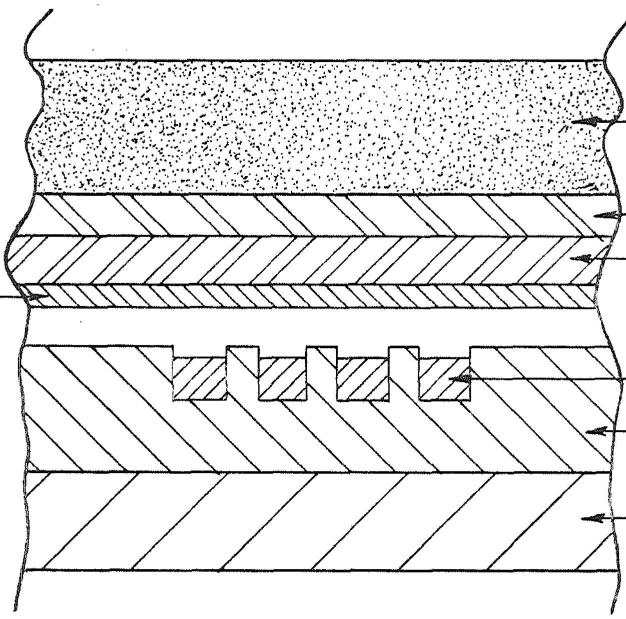


FIGURE 15. COMPONENT ARRANGEMENT FOR RIB-TO-LINER WELDING OPERATION

The rib-shell structure was previously fabricated using the integral-rib techniques.

FABRICATION OF SIX- AND NINE-RIB PANELS

This phase of the Task I effort had two objectives: (1) to determine whether the process developed for fabricating three-rib panels could be employed to fabricate larger panels for detailed testing, and (2) to evaluate the effects of changing the rib dimensions on the quality of welds produced in a panel configuration.

Nine-Rib Panels

A number of nine-rib panels, having the configuration shown in Figure 3, were fabricated to determine whether the process could be used in the production of larger components. Duplicate specimens were made in order to evaluate the reproducibility of the process.

These panels were fabricated using the techniques developed in welding three-rib panels. Whereas only two material combinations (304 SS – Hastelloy X and Alloy 718 – Hastelloy X), were employed in the three-rib panels, panels fabricated in this effort were made from each of the materials combinations listed earlier. The panels so fabricated were subjected to detailed nondestructive testing, and in addition several of the panels were burst tested to failure.

The panels were welded using the methods developed in successfully fabricating the three-rib panels. As in that work, the ribs were alternated with mild-steel spacer tooling bars and held to a thin steel support plate with double-sided tape. The ribs were slightly higher than the tooling bars, producing a vertical step of 0.005 inch. After the first welding operation, the rib-and-shell composite plates were flattened and then used used as the base component in the liner-to-rib welding step. The explosive-welding parameters used to fabricate the nine-rib panels are presented in Table 5.

TABLE 5. WELDING PARAMETERS USED IN NINE-RIB PANEL FABRICATION

Welding Operation	Standoff Gap, in.	Explosive Thickness, in.	Experiments
	304 Stainless Steel Panels		
Rib-to-shell weld	0.068	3/4	S-1 through S-6
Hastelloy X liner-to-rib weld	0.050	9/16	S-1, -2, -4, -5
TD Nickel liner-to-rib weld	0.068	9/16	S-3, S-6
	Allvac 718 Panels		
Rib-to-shell weld	0.100	11/16	A-1 through A-9
Hastelloy X liner-to-rib weld	0.070	3/4	A-1, -2, -4
TD Nickel liner-to-rib weld	0.068	5/8	A-3, A-6,
Allvac 718 liner-to-rib weld	0.068	3/4	A-8, A-9

One small change was made in the welding operation – the mode of initiation was changed. Because of the larger widths of the nine-rib panels, it was deemed necessary to initiate the welding charge in a linear mode rather than in the point mode used earlier. This linear detonation was accomplished by means of a line-wave detonator, a sheet of plastic explosive manufactured so as to convert a point detonation (from a detonator) to a line detonation. By this means, a detonation front which propagated perpendicular to the ribs was insured.

A total of 15 nine-rib panels were fabricated, and all of these panels appeared sound in the as-welded condition. Except for those panels which had TD Nickel liners, the mild-steel spacer and support tooling was successfully removed from the panels by acid leaching (50 percent nitric acid at 200 F) and the panels were prepared for detailed evaluation. Typical panels are shown in Figure 16.

A chemical compatibility problem was encountered with the TD Nickel liners. As this problem had been anticipated, compensating steps were taken during fabrication of the panels with these liners. Prior to their use in the fabrication of panels, each of the liners had been clad explosively on one side with a thin layer of Type 301 stainless steel. The coated side of the liner was then welded to the ribs in the liner-to-rib welding step.

It was hoped that the stainless steel cladding would isolate the internal surface of the TD Nickel from the leaching acid, and that the external surface could be protected by a suitable organic coating. However, the several external coatings which were attempted failed to protect the nickel, generally because they did not adhere well to the liner at

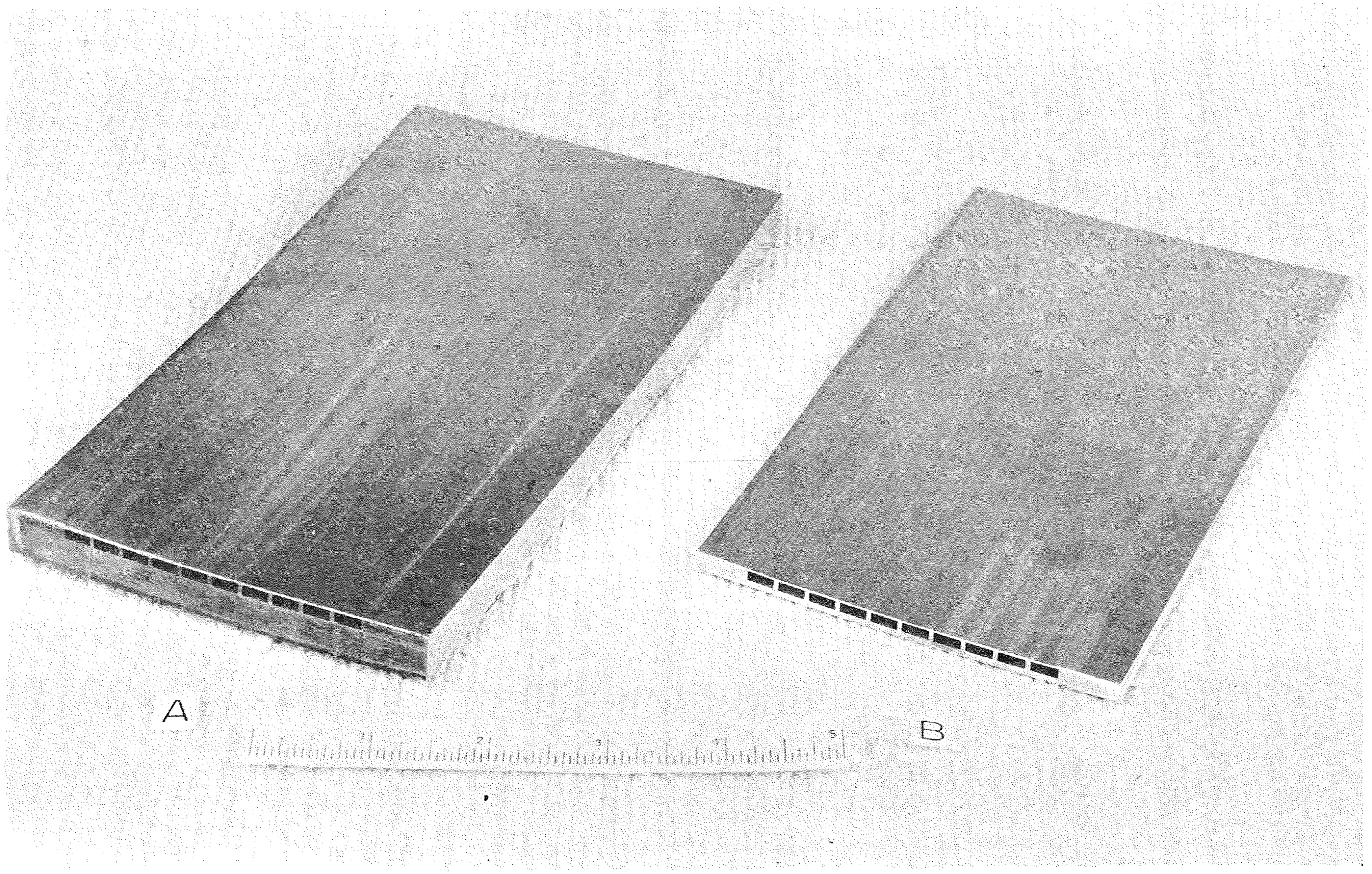


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FIGURE 16. EXPLOSIVELY FABRICATED PANEL SPECIMENS

a. Type 304 SS rib-shell structure with a Hastelloy X liner
b. Allvac 718 rib-shell structure with a Hastelloy X liner

the elevated temperature and permitted the acid to gain access to the TD Nickel. For this reason, no panels with TD Nickel liners were available for additional testing.

Six-Rib Panels

To access the effects of changing the rib configuration on the quality of panels produced, a number of six-rib panels were fabricated. The 304 stainless steel-Hastelloy X materials combination was used in this work. The number of ribs in these panels was reduced to six from the nine used in the previous panel-welding experiments. The use of a smaller number of ribs reduced the complexity and time required to set up and fabricate the panels, yet still produced a panel sufficiently wide to evaluate the effects of changing the rib configuration.

Two types of experiments were run, each for examining the effect of changing a different rib variable. One of these was performed to determine whether large tolerances on the rib height would effect the quality of welding in the panels, and the height of the ribs was varied. The second was performed to determine the quality of welds produced using ribs whose height changed from one end of the panel to the other. These tapered-rib experiments were designed to simulate a configuration which could be necessary in nozzle fabrication.

In first series of experiments three panels were fabricated using ribs which had heights of 0.115 and 0.125 inch. The assembly and welding procedures used in these experiments were the same as those used to fabricate the three-rib panels. In these experiments, however, the height of the tooling was reduced from 0.115 to 0.110 inch so as not to interfere with welding of the shorter ribs.

In the second series of experiments, panels were fabricated which had tapered-height ribs and cooling channels. The ribs and spacer-tooling components used in these experiments were uniformly tapered from one end to the other. The height of the ribs was 0.120 inch at one end and 0.090 inch at the other. The other components were identical to those used in earlier experiments. The standoff gap used in the rib-to-shell welding operation was also tapered and varied from 0.068 inch at the large end of the ribs to 0.058 inch at the other. All other procedures and parameters were identical to those used earlier.

The panels which incorporated these two modifications were examined after welding. No significant differences were found in the quality of the welds so produced. The panels looked essentially the same as those shown in Figure 16 except for having six ribs instead of nine. These findings indicate that differences in rib height as great as 0.010 inch can be tolerated in the rib-welding operation, and also show that tapered-height channels can be fabricated by this process.

TESTING AND EVALUATION OF PANEL SPECIMENS

The six- and nine-rib panels fabricated above were evaluated using a variety of nondestructive and destructive test methods. Ultrasonic test techniques and internal hydrostatic proff testing were used as nondestructive methods, and hydrostatic burst testing was used to determine the ultimate strengths of the fabricated panels.

Nondestructive Testing

It was originally planned to utilize thermography as one method to evaluate the weld integrity of the explosively welded panels. However, this technique was not pursued because the results obtained in a parallel NASA-sponsored program* were not encouraging In this study, panels of a configuration similar to those employed here were examined using thermographic methods, and it was found that use of either a heat-sensitive fluid or a heat-sensitive crystal could not resolve areas of poor welding in otherwise welded panels.

Ultrasonic Testing

Ultrasonic testing was used to determine the completeness of welding in panels fabricated by explosive welding. A direct transmission method shown to be sensitive enough to resolve nonwelded areas as small as 0.020 inch in diameter, was employed in this work.

In this method, the panel to be tested was held in an adjustable fixture, immersed in water, and positioned between two ultrasonic crystals. One of these crystals emitted a signal which passed through the sample and was received by the second. The strength of the received signal served as a direct measure of the degree of contact between the metal components in the panel. A nonwelded area transmitted only a small signal, while one which was welded transmited most of the energy it received. It should be noted that while this method could be used to differentiate areas of welds from areas which were not welded, since it responds to changes in acoustic impedance (i.e., gaps), it could not be used to measure the strength of a weld, since no gap would be seen even in a weak weld.

The utility and sensitivity of this method were determined with a number of calibration panels prepared by both explosive welding and gas-pressure bonding. These calibration samples were panels which had either been fabricated with variously sized intentional defects or had defects (holes) drilled laterally into them after fabrication. Results obtained from these calibration panels showed that this nondestructive test method could resolve nonwelded areas as small as 0.020 inch in diameter.

Several explosively welded panels were ultrasonically tested using this method. The testing showed that explosively welded panels of both 304 stainless steel-Hastelloy X and Alloy 718-Hastelloy X were completely welded, as no weld defects were found in any of the samples.

Hydrostatic Proof Testing

Hydrostatic proof testing was required of the panels fabricated by explosive welding. This internal pressurization simulated the conditions under which the components which the flat panels represented operated, and so served as a first test of the practical integrity of the panels. Eight panels were proof tested to several times the required 500-psi pressure without failure of any of them.

*Ashurst, A. N., Goldstein, M., and Ryan, M. J., "Development of Advanced Fabrication Techniques for Regeneratively Cooled Thurst Chambers by the Gas-Pressure-Bonding Process", NASA CR-72795, July, 1970.

Both six- and nine-rib panels were tested. A problem was initially encountered in sealing the ends of the panels so that the panels could be pressurized. Several mechanical methods were used in efforts to adequately seal the ends of the specimens, but were not successful because the ribbed cross section of the specimens provided insufficient bearing area for sealing against the 500-psi pressure. The sealing technique which ultimately was used required fusion welding of steel end-closure fittings to both ends of the panels. One fitting on each specimen served as a manifold and allowed fluid to pass into all channels of the specimen. Fusion welding of the end closures proved to be a difficult problem because of the thickness differences in the shell, liner, and end fittings. Complete sealing of each panel specimen was accomplished only after repeated efforts to repair leaks.

Each panel specimen was connected to a hydraulic pressure system rated for 3000 psi. A dye-penetrant oil, Zyglo-Pentex-Type ZL-2* was used as the pressurizing fluid. A dial indicator was used to measure the outward motion of the liner midway between two ribs as the panel was pressurized.

In a typical pressure test, the internal pressure was slowly increased in increments of 100 psi until a pressure of 500 psi was reached, and then in increments of 250 psi until several times the proof-test pressure was attained. At each increment of pressure, the specimen was visually examined using an ultraviolet light for evidence of the penetrant oil, which would indicate failure of the specimen. The deflection of the liner was also noted at each interval of pressure.

All of the panels were pressurized to 1500 psi (three times the required proof-test pressure of 500 psi) without failure or permanent deformation of the components. The test results indicate that the panels produced by explosive welding are sound, strong, and have high integrity.

Destructive Burst Testing

The pressurization of the panels described above was continued, and several six- and nine-rib panels were tested to destruction using hydrostatic burst testing. By this means, the qualitative strengths of the welds produced by the explosive-welding process were determined. The panels were pressurized until failure occurred.

The lowest pressure at which a panel failed was 1750 psi, and three others failed at pressures between 2250 and 2750 psi. Four of the panels were tested to 3000 psi without failure. Two of these panels were further pressurized to failure. One of them failed at 5100 psi, and the other reached a pressure of 5400 psi before failure.

Each of the failures was directly or indirectly connected with the end-closure welds. Several of the failures occurred in these end closures, while the other failures were initiated in the rib-to-shell weld at the heat-affected zone from the fusion-welding operation. The stress state during hydrostatic loading then caused the deflection of the rib and liner and the failure propageated through the lower ductility bond zone as a crack.

*Trade name for product manufactured by the Magnaflux Corporation.

Measurement of the liner deflection during testing showed deflections of 0.001 to 0.002 inch for pressures of 3000 psi. These deflections were recovered on depressurization, indicating that the design kept the liners in the elastic regime at this high pressure.

The liner deflections for the two specimens tested to above 5000 psi showed that the liners had plastically deformed about 0.002 to 0.003 inch in most areas. Some regions next to the welded end closure were found to have deflected more than 0.010 inch. However, this is not a problem for the operating pressures that are presently required for rocket engines. This latter result indicates that the heat generated by fusion welding can have an adverse effect.

SUMMARY OF RESULTS

All of the materials combinations of interest could be welded explosively using powdered-dynamite explosive loaded to thicknesses of 9/16 inch to 1-5/16 inch, depending on the particular combination. The standoff gaps required were 1/2 to 1 times the thickness of the cladder plate-support plate thickness.

All of the materials except TD Nickel were work hardened considerably by the explosive-welding operation. The work-hardened regions extended for about 0.030 inch on either side of the weld interface.

The welds evaluated in tensile shear tests were in all cases at least equal in strength to the parent plates, and in several cases they were stronger.

Ductility of the welds was determined by bend tests, and it was found that the welds made with aged Alloy 718 exhibited considerably reduced ductility at the weld zone.

On the basis of a limited number of experiments, it does not appear feasible to explosively weld panel components which have been plasma sprayed with a ceramic coating without damaging the coatings.

In welding ribbed components, it was found necessary to increase the flat-plate welding parameters in order to produce sound welding over the full area of the ribs. As an example, in welding flat plates of 304 stainless steel to itself, welding parameters of 11/16 inch of explosive and 0.060-inch standoff were used, whereas in welding stainless steel ribs to a similar shell, parameters of 3/4 inch of explosive and 0.068-inch standoffs were required.

Removal of the mild-steel tooling from panels having TD Nickel liners presented serious chemical-compatibility problems which were not solved in this task.

Variations in height of the ribs of ±0.005 inch do not affect the strength of the welds produced using fabrication methods identical to those used for panels with more carefully controlled rib heights.

Panel specimens containing channels which are longitudinally tapered in height from one end to the other can be fabricated explosively, but the standoff gap must be tapered accordingly.

Explosively fabricated panel specimens can withstand internal pressures of at least several times the 500-psi maximum operating-pressure level anticipated for current thrust-chamber designs. The lowest pressure at which failure occurred was 1750 psi, while two panels were pressurized to over 5000 psi before failure. In each case, the failure occurred in or near the fusion-welded end closures, which indicates that heat from fusion welding can adversely affect the behavior of the explosive welds.

TASK II. FABRICATION OF CYLINDRICAL SPOOLPIECES

OBJECTIVE, APPROACH, AND COMPONENTS

The objective of Task II was to fabricate two cylindrical spoolpieces having the design specified in NASA-Lewis Drawing No. CD621169, Amendment A. Figure 17 is a cutaway sketch of the spoolpiece showing the various chamber components and their location. On the basis of the results of Task I, the two spoolpieces were made from the combination of materials tabulated below.

Spoolpiece Component	Spoolpiece Materials	
	Chamber 1	Chamber 2
Shell and plenum	304 SS	Alloy 718 (age hardened)
Ribs	304 SS	Alloy 718 (solution treated)
Liner	Hastelloy X	Hastelloy X
End cover	Hastelloy X	Hastelloy X

Fabrication of each prototype spoolpiece involved three different explosive-welding operations and four separate explosive welding steps. The initial part of this task was concerned with developing the technology to successfully accomplish these welding operations. This technology was applied in fabricating the two cylindrical spoolpieces during the last part of this task.

PRELIMINARY WELDING DEVELOPMENT

The cylindrical design of the spoolpiece requires that the shell, rib, and liner components be assembled and explosively welded in a circular configuration. The purpose of these preliminary experiments was to modify and extend the technology used to fabricate flat panels in Task I and apply it to the circular geometry of the spoolpiece. These development efforts were concentrated on the three explosive-welding operations involving rib-to-shell, liner-to-rib, and end cover-to-plenum joints. The welding experiments were designed to simulate as closely as possible the conditions expected in fabricating the spoolpieces.

Rib-to-Shell Welding Experiments

The most successful and feasible technique used in fabricating flat panels during Task I involved accelerating and welding ribs and tooling to the shell as a single unit. This procedure was used in the present experiments in welding curved segments of ribs and tooling to a curved shell. In most of the experiments, 304 SS rib and shell components were welded, but Alloy 718 components were welded in some later experiments.

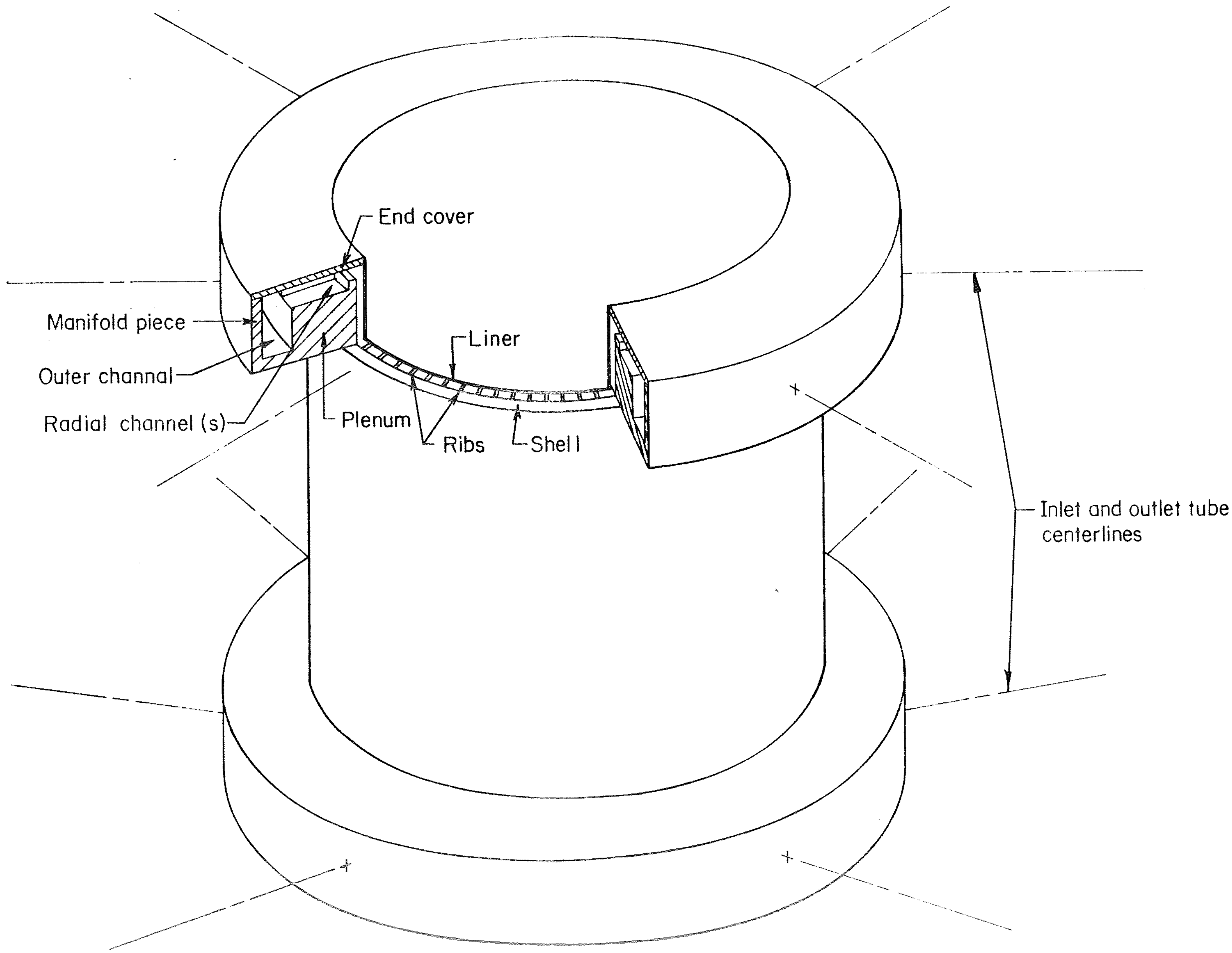

FIGURE 17. SCHEMATIC SHOWING DETAIL OF TYPICAL SPOOLPIECE

Preparation of Components

In these experiments the spoolpiece shell component was simulated by a cylinder supported by an external, one-piece die. The simulated shell either was machined from 304 SS seamless pipe or fabricated from Alloy 718 sheet which was rolled and fusion seam welded. The shells were nominally 3/16 inch thick and fit snugly inside a 4140 steel forging, measuring 10 inches in ID by 16 inches in OD by 9 inches high. The size of the simulated shells closely approximated that of the spoolpiece shell. The arrangement also permitted periodic replacement of a shell.

Ribs were machined from nominal 0.04-inch-thick sheet and finished by grinding them to 1/8 inch high by 12 inches long. Support tooling for the ribs was fabricated from hot-rolled steel pipe. Each tooling cylinder was machined to 12 inches long with a total wall thickness of 3/16 inch. The outside diameter was varied somewhat from one cylinder to another to maintain a nominal 3/16-inch gap between the outside cylinder surface and the inside surface of the shell. Each cylinder was slotted on its outside surface with approximately 102 equally spaced grooves oriented parallel to the cylinder axis. The grooves were machined just deep and wide enough to hold the ribs firmly in place, with the rib surfaces extending out of the grooves about 0.010 inch. Four tooling cylinders were made; two of these were sectioned into four 90-degree segments for use in separate experiments. The remaining two were left integral.

Assembly and Welding Procedures

Six experiments were conducted using 90-degree segments of 304 SS ribs and 304 SS shells. Three segments were welded to each shell in separate experiments. These experiments were designed to verify parameters for welding ribs to the shell. In setting up each experiment, ribs were fitted in the slots of the tooling sement and this assembly was positioned with a constant gap between the ribs and shell. A Zerolite* center mandrel was machined to form an annulus behind the tooling segment and to fill the remaining volume within the shell. Figure 18 shows the component arrangement at this stage of assembly. The center mandrel, like the tooling segment, extended about 2 inches above and 1 inch below the shell. The annulus between the tooling segment and plug was loaded with Trojan SWP-1 explosive to a density of 16 g/in.^{3}. The explosive charge was detonated around its upper surface by a line-wave detonation arrangement consisting of an arc segment of plastic-sheet explosive and a detonator positioned at the apex of the arc which was located at the centerline of the Zerolite center mandrel.

Two additional experiments were conducted later using complete (360-desgree) segments of ribs and tooling. In one of these the ribs and shell were 304 SS, and in the other Alloy 718 ribs were welded to an Alloy 718 shell. After the ribs were fitted into the tooling-cylinder grooves, the cylinder was positioned concentric with respect to the shell, forming an annular standoff gap between them. A solid center mandrel of Zerolite was machined and positioned inside the tooling cylinder, forming another annular gap in which the explosive charge was loaded. A circular line-wave detonation arrangement, made from a disk of plastic-sheet explosive and a detonator located in the center of the disk, was used to simultaneously detonate the annular explosive charge over its top surface.

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*A low-density, pressed insulating material.

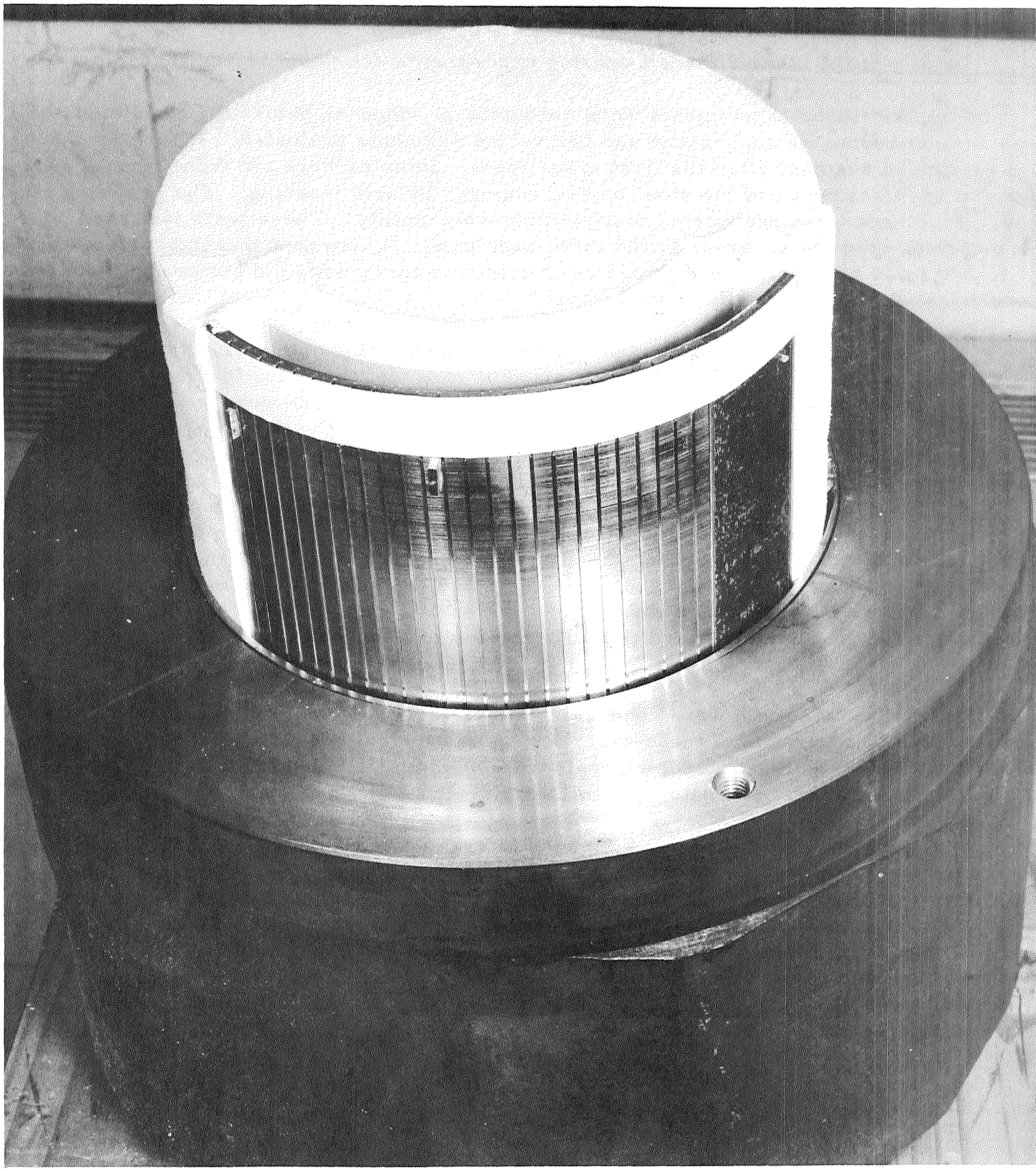

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FIGURE 18. PARTIALLY ASSEMBLED SETUP FOR EXPLOSIVELY WELDING A 90-DEGREE RIB-TOOLING SEGMENT TO A SIMULATED SHELL

The segment of ribs and tooling and the Zerolite center mandrel have been pulled from the shell to show these components more clearly.

Evaluation and Discussion of Results

Details of the eight-rib shell welding experiments are summarized in Table 6.

The first three experiments were conducted in sequence before the simulated shell was removed from its support die and the welded segments evaluated. Figure 19 shows the as-welded segment from the first experiment. Samples were cut from several locations in each segment and the steel tooling removed by acid leaching. The resulting rib-shell structures were peel tested to determine weld quality. These tests indicated poor or marginal welds in all areas of the three segments. It appeared that the combinations of standoff gap and explosive loadings used in these experiments did not produce collision conditions sufficient to produce good welds.

The next three, essentially identical, experiments (Experiments 4, 5, and 6 in Table 6) were conducted in which larger standoff gaps and explosive loadings were used. These segments were not evaluated until after Hastelloy X liners were welded to them, as will be described later. Samples from different areas of the three segments were then removed and their steel tooling removed by acid leaching. Metallography and peel tests were used to assess weld quality in these samples. The rib-to-shell welds from these samples exhibited improved resistance to peeling over those of the previous series of experiments. Good welds extended to within 0.5 to 1.0 inches of the segment top edges and to within 0.5 inch of the segment bottom edges. Figure 20 shows typical transverse and longitudinal views of a rib-shell weld interface in a sample from Experiment 6. The weld interfaces in these samples (longitudinal view) were for the most part straight, although some contained periodic regions of a ripple pattern indicative of a good weld.

Experiments 7 and 8 were conducted using integral, 360-degree segments of ribs and tooling. The purpose of these experiments was to verify the results of the previous experiments in which 90-degree segments were welded. Rib and shell components were 304 SS in Experiment 7 and Alloy 718 in Experiment 8.

Ring sections were cut from both ends of each segment, again after the Hastelloy X liners were welded to them. After removing the steel-channel tooling, these sections were evaluated by metallography and peel tests. Good rib-to-shell welds were found in almost all interior locations in these segments. Areas of poor weld which extended 1/2 to 1 inch from the top or detonation end of the shells and 3/4 inch from the bottom end were found in both segments. This weld distribution, as well as the strength of the welds and their interface appearance, was very much like those of the previous series of three experiments.

Liner-to-Rib Welding Experiments

It was found necessary to support the thin Hastelloy X liners in fabricating the flat panels in Task I. This was accomplished by laminating the liner with steel sheet and accelerating this combination as a unit when welding the liner to the panel ribs. This technique was used in the present experiments involving circular components.

TABLE 6. SUMMARY OF PRELIMINARY RIB-TO-SHELL AND LINER-TO-RIB WELDING EXPERIMENTS

			Chamber-Component Materials			Explosive-Welding Parameters		
							Explosive	
Experiment	Segment	Segment Size, deg	Shell	Rib[a]	Liner[b]	Nominal Standoff Gap, in.	Type[c]	Nominal Charge Thickness[d], in.
				Rib-to-Shell Experiments				
1	1	90	304 SS	304 SS	--	1/8	T70C	7/16
2	2	90	304 SS	304 SS	--	1/16	T70C	15/32
3	3	90	304 SS	304 SS	--	1/16	T70C	15/32
4	4	90	304 SS	304 SS	--	1/8	T70C	23/32
5	5	90	304 SS	304 SS	--	1/8	T70C	23/32
6	6	90	304 SS	304 SS	--	1/8	T70C	23/32
7	7	360	304 SS	304 SS	--	3/16	SWP-1	23/32
8	8	360	Alloy 718[e]	Alloy 718[f]	--	3/16	SWP-1	23/32
				Liner-to-Rib Experiments				
1	4	90	--	304 SS	Hastelloy X	1/16	SWP-1	7/16
2	5	90	--	304 SS	Hastelloy X	1/16	SWP-1	7/16
3	6	90	--	304 SS	Hastelloy X	1/16	SWP-1	7/16
4	7	360	--	304 SS	Hastelloy X	1/16	SWP-1	7/16
5	8	360	--	Alloy 718[f]	Hastelloy X	1/16	SWP-1	7/16

(a) Ribs and tooling fixture were accelerated in the rib-shell welding experiments; the tooling fixture was 3/16 inch thick.
(b) Liner and steel composite, 0.082 inch thick, was accelerated in liner-rib welding experiments.
(c) Both T70C and SWP-1 have equivalent properties.
(d) The charge thickness actually is the width of the annular gap and is given to the nearest 1/32 inch.
(e) Age hardened.
(f) Solution treated.

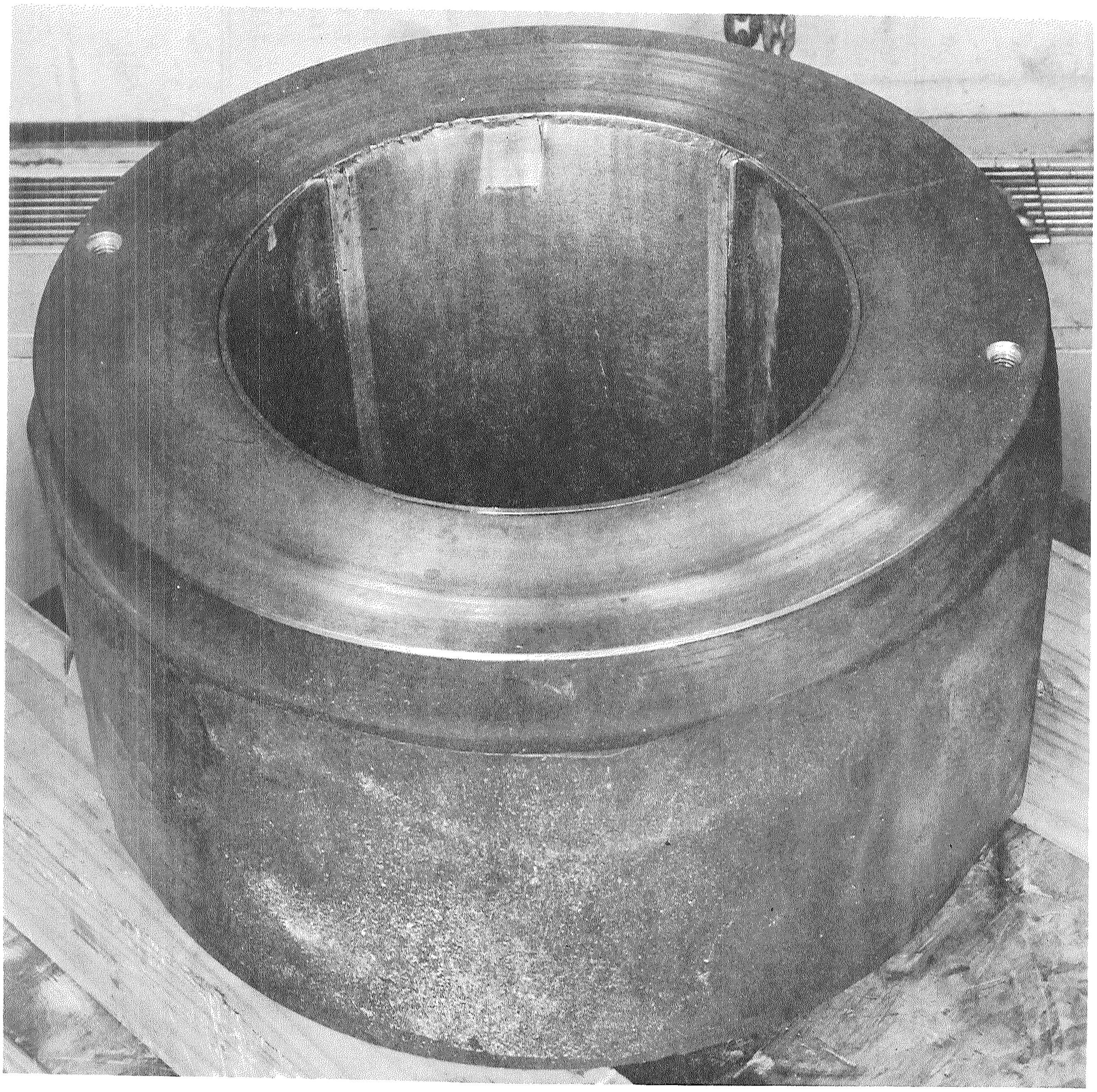

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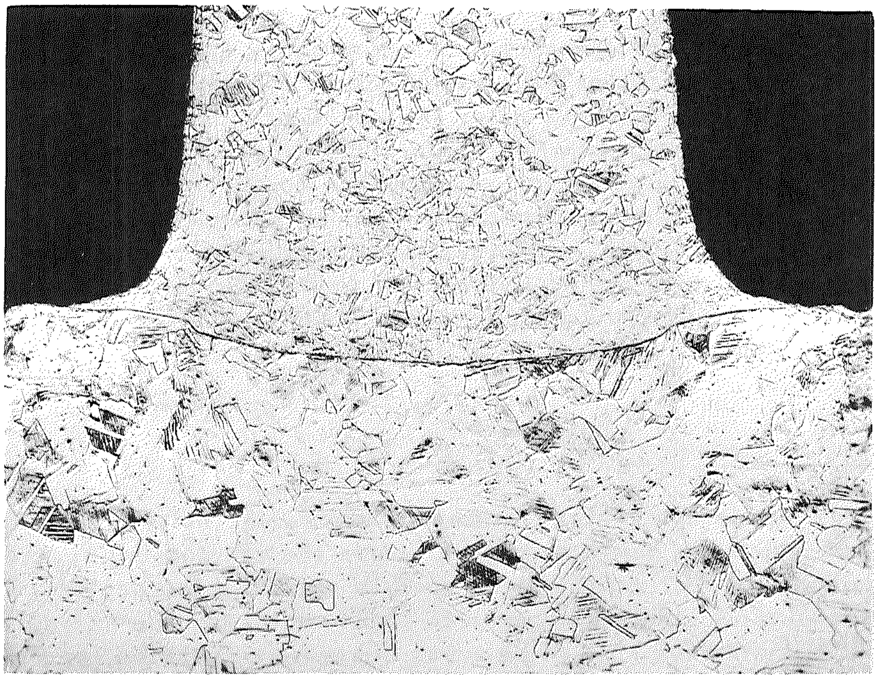
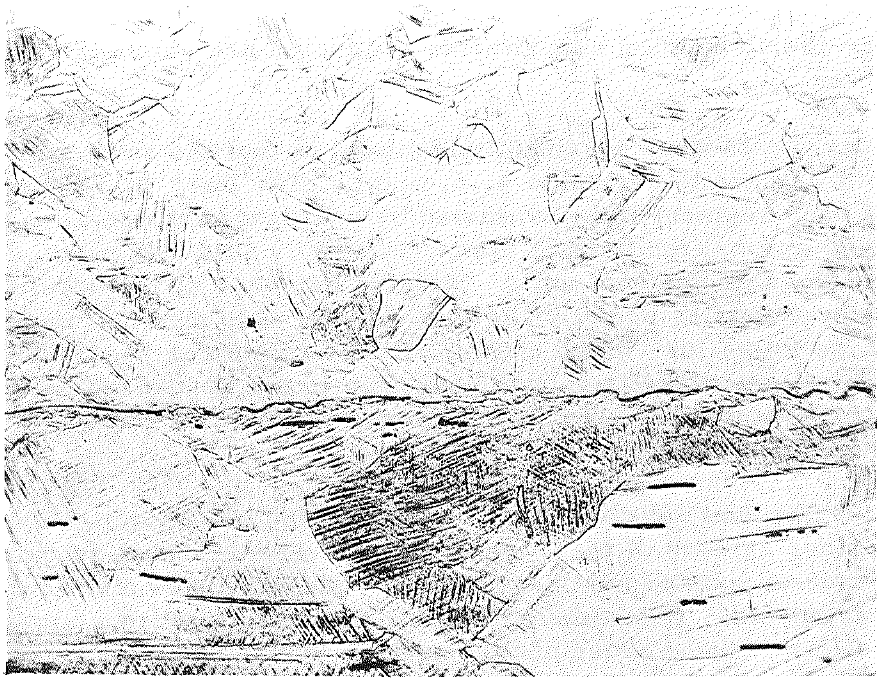
FIGURE 19. NINETY-DEGREE SEGMENT OF RIBS AND TOOLING EXPLOSIVELY WELDED TO A SIMULATED THRUST-CHAMBER SHELL USING SETUP SHOWN IN FIGURE 18



50X 8D466

a. Transverse View



100X 8D468

b. Longitudinal View

FIGURE 20. EXPLOSIVE WELD PRODUCED BETWEEN A RIB AND SIMULATED SHELL

Preparation of Components

Five previously welded rib and tooling segments (Segments 4, 5, 6, 7, and 8 in Table 6) were used in these liner-to-rib welding experiments. In preparing these segments for welding Hastelloy X liners to their ribs, 1/16 inch of steel tooling was machined away to expose the back surfaces of the ribs. This machined surface then was treated with a solution of water and nitric acid to reduce the height of the steel tooling 0.005 to 0.01 inch below the rib surfaces. Sheets of 0.02-inch-thick Hastelloy and 1/16-inch steel were laminated, rolled into cylinders with Hastelloy on the outside, and fusion seam welded. The curvature of the cylinders was made to match that of the machined rib surfaces. These laminated cylinders were either cut into 90-degree segments or left integral.

Assembly and Welding of Components

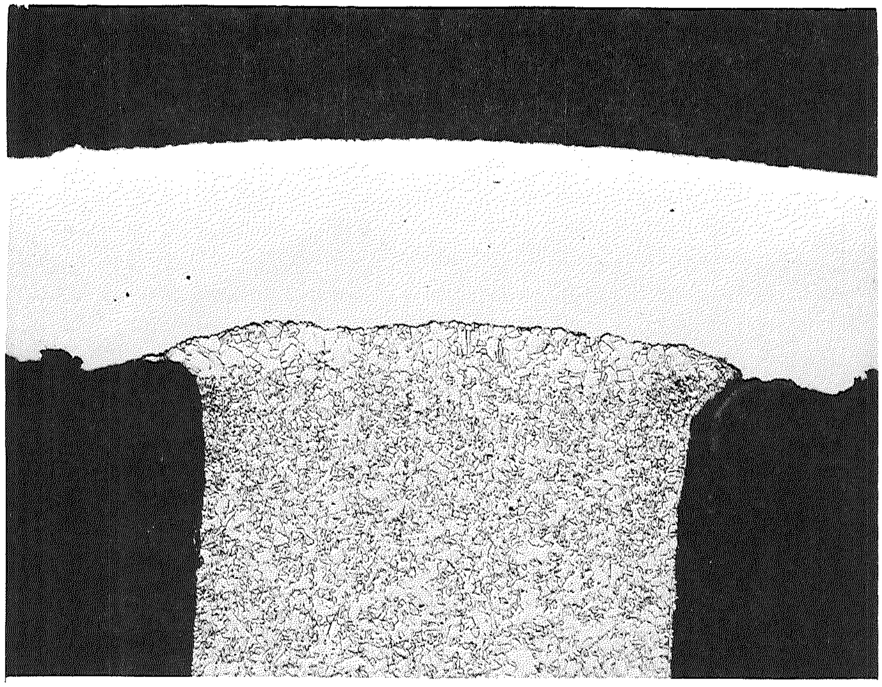
The 90- and 360-degree Hastelloy-steel laminates were assembled for welding to the rib-tooling segments in much the same manner as were the rib-tooling segments for welding them to the simulated shells. Shims were used to maintain the desired liner-rib standoff gaps. Zerolite center mandrels machined to form annuli for the explosive charges which were initiated using the same line-wave schemes described for the earlier rib-shell experiments.

Evaluation and Discussion of Results

Details of five liner-to-rib welding experiments conducted are summarized in Table 6.

The first three experiments were essentially identical in that the same parameters were used to weld Hastelloy liners to Segments 4, 5, and 6. The liner-to-rib welds from several samples of each segment were evaluated by peel tests and metallographic examination after the steel-channel tooling had been removed by acid leaching. Good welds were found in all of the samples evaluated. Welding extended up to within 1/8 inch of the top and bottom edges of the segments. The liner-to-rib weld strength everywhere exceeded the strength of the Hastelloy, which always failed first during peel testing. Figure 21 shows the liner-rib interface from a typical area in the second experiment. The rippled interface in the longitudinal view is one characteristic of a good weld, and this feature was noted in all the samples.

Experiments 4 and 5 involved 360-degree components with 304 SS and Alloy 718 ribs, respectively. All other aspects of these experiments were the same as those of the first three. No evidence of poor or marginal liner-to-rib welds was found in any areas of the two welded segments. The peeling behavior and metallographic appearance of these welds were not different from those of the previous 90-degree segments. Figure 22 shows part of the stainless steel/Hastelloy X 360-degree segment whose liner was welded in the fourth experiment. Other parts of this segment were destroyed in evaluating the rib-to-shell and liner-to-rib welds. The Alloy 718/Hastelloy X segment from Experiment 5 was identical in appearance and was later proof tested and forwarded to NASA-Lewis in place of the Alloy 718/Hastelloy X spoolpiece which failed during the first explosive-welding operation.

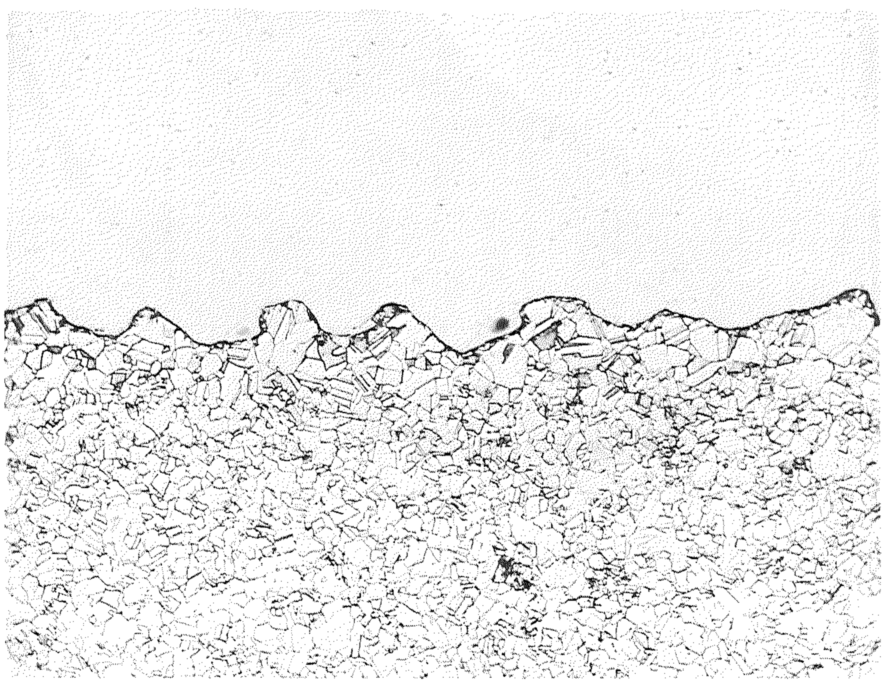


Hastelloy X liner

304 SS rib

50X 8D576

a. Transverse View



Hastelloy X liner

304 SS rib

100X 8D573

b. Longitudinal View

FIGURE 21. EXPLOSIVELY WELDED INTERFACE BETWEEN LINER AND RIB IN CYLINDRICAL SPECIMEN

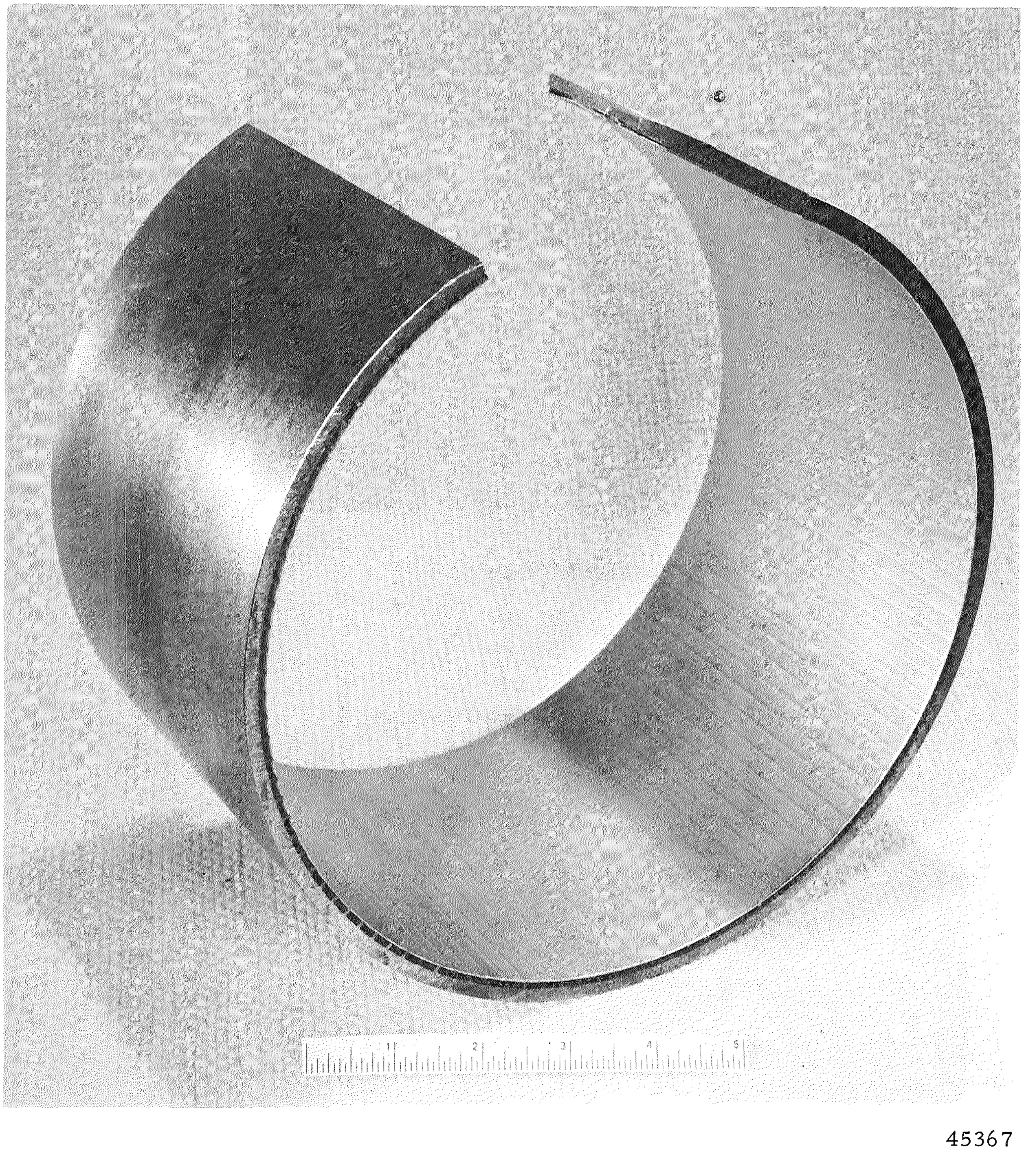


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FIGURE 22. SECTION OF 360-DEGREE SEGMENT OF 304 SS RIBS AND HASTELLOY X LINER EXPLOSIVELY WELDED TO A SIMU-SIMULATED 304 SS SHELL

The entire segment has been removed from the support die and the steel channel tooling leached out.

End Cover-to-Plenum Welding Experiments

The third and final explosive welding operation required for fabricating the cylindrical spoolpiece involves joining end covers to the plenum sections at both ends of each chamber. In this welding operation, the end cover should not only weld to the plenum surface, but to the narrow end surfaces of the liner and ribs as well. This is necessary to form a leaktight system for the cooling fluid to be circulated through the spoolpiece. The technique envisioned for welding an end cover to the thrust chamber is illustrated in Figure 23. The circular disk of Hastelloy X sheet is to be welded to the plenum surface which has been machined to the required channel configuration. A centerline detonation scheme insures that welding will be accomplished in a symmetrical fashion from the inside to the outside of the plenum surface. In welding the end cover in this manner, the collision region will pass over several junctions separating the liner, ribs, tooling, and plenum components. It is known that such junctions can disrupt welding for some distance downstream from the junctions.

These preliminary experiments were designed to duplicate the conditions expected in welding end covers to the spoolpieces. The experiments were conducted to establish parameters or conditions for welding the end cover to the several chamber components on the plenum surface. It was also of interest to determine the effects of junctions on welding.

Preparation of Components

Flat components of Hastelloy X and 304 SS were used in these experiments. The 3/16-inch Hastelloy X represented the end cover, while 1/2-inch 304 SS represented the plenum section of the chamber. The plenum component was machined to accommodate 0.020-inch-wide Hastelloy X strip and mild-steel inserts, which represented the liner and tooling, respectively. The liner and tooling pieces were oriented with respect to the welding direction as they would be in welding the end covers to the thrust chambers. Three sets of components were prepared for three experiments.

Assembly and Welding Procedures

Components for all three end-cover-weld-simulation experiments were assembled and welded in much the same manner. The Hastelloy X and mild-steel inserts were positioned in the composite base plate representing the plenum (Figure 24). Hastelloy sheet was supported above and parallel with the composite base. A layer of Trojan SWP-1 granular explosive was placed on top of the Hastelloy. The charge was initiated from one end so that welding proceeded in a direction normal to the 0.020-inch-wide Hastelloy strip in the composite base. In the first experiment the tooling and plenum surfaces of the base were not covered. In the second experiment, a 0.020-inch piece of Hastelloy was attached to the internal-support-die surface immediately upstream from the Hastelloy strip. This procedure was repeated in the third experiment, and the mild-steel tooling surfaces also were covered with 304 SS foil.

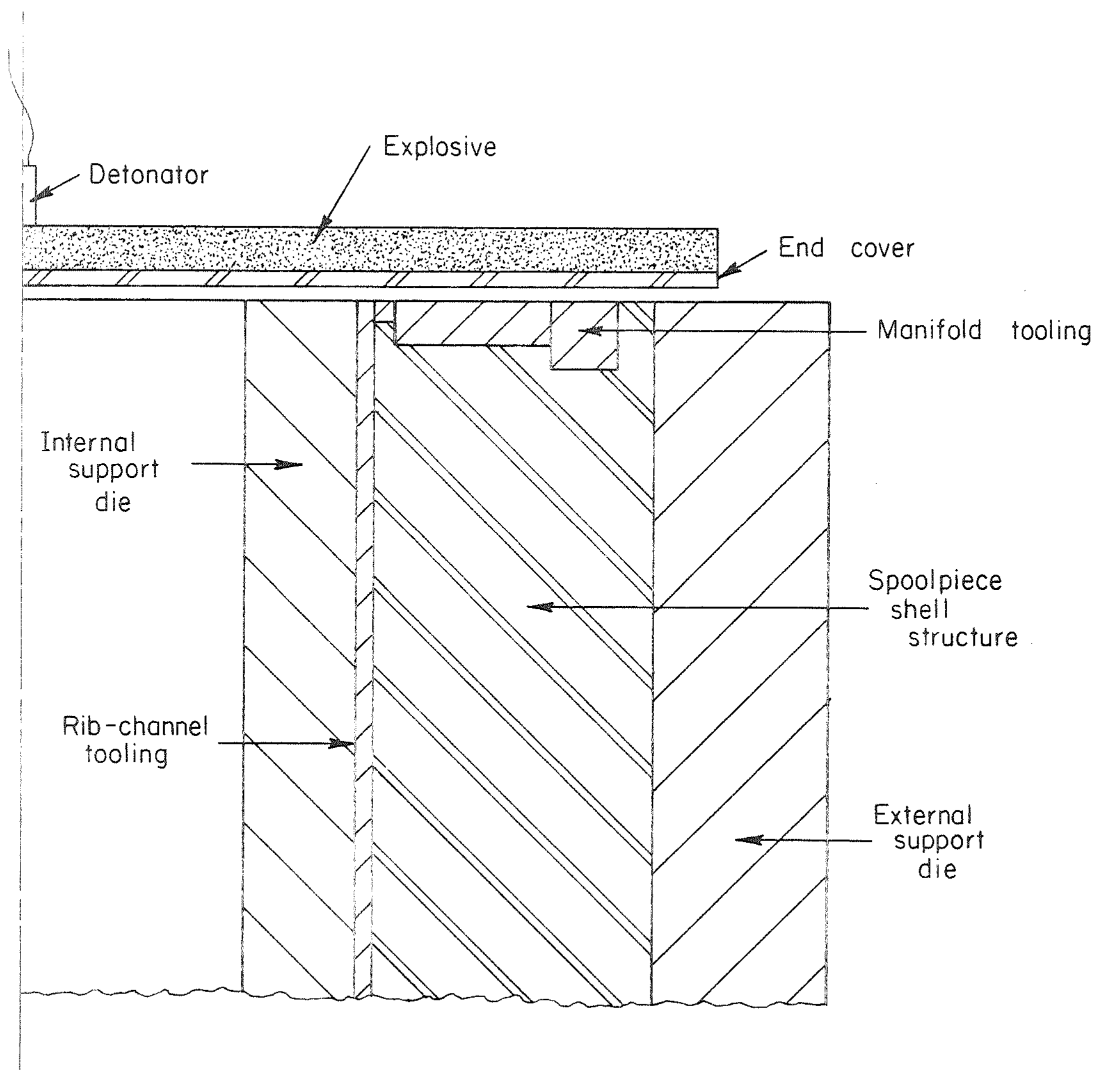


FIGURE 23. SETUP FOR WELDING END COVER PLATES TO SPOOLPIECE PLENUM SURFACES

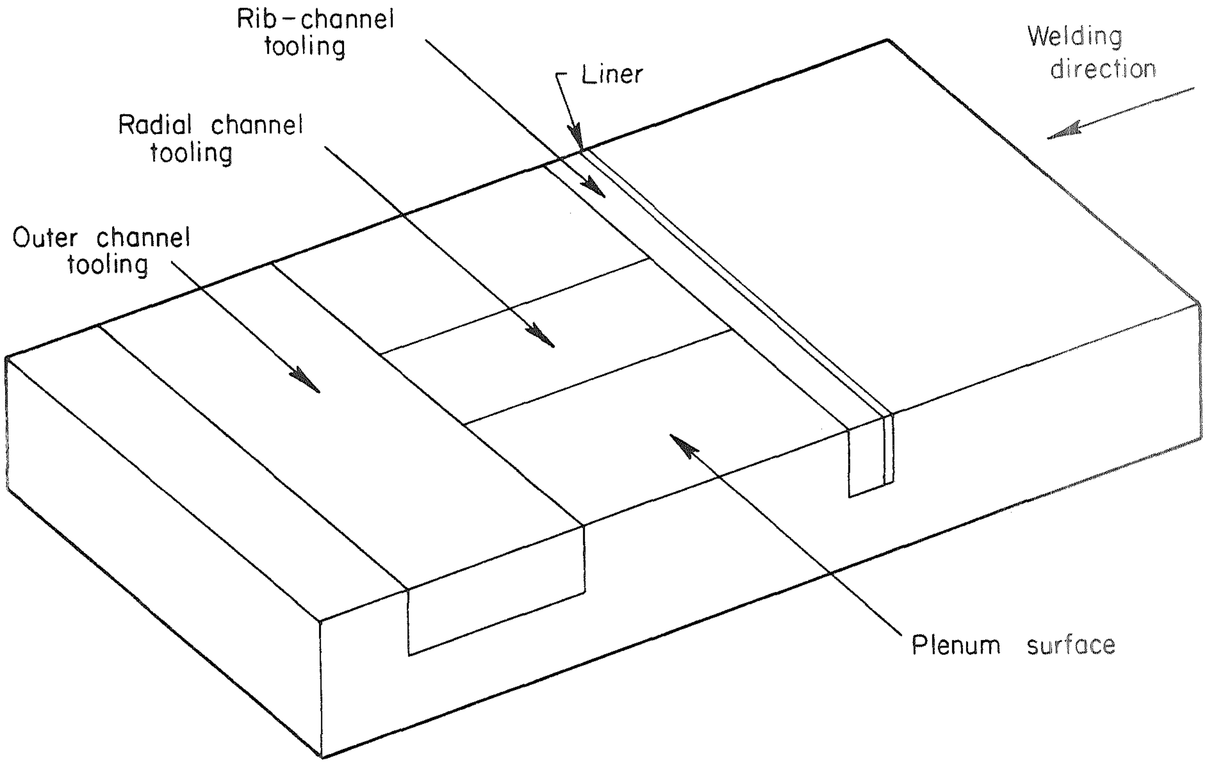


FIGURE 24. COMPOSITE BASE PLATE USED IN SIMULATED END-COVER-WELDING EXPERIMENTS

Evaluation and Discussion of Results

The specimens from the three welding experiments were sectioned along their length, and samples from each were peel tested and metallographically examined.

A 3/16-inch standoff gap between the Hastelloy and the composite base and a 5/8-inch-thick layer of explosive were used in the first experiment. Good welds were produced between Hastelloy X and 304 SS in most areas. Exceptions were regions immediately downstream from junctions separating the steel tooling and the Hastelloy X liner from the 304 SS plenum. Poor or marginal welds extended 1/4 to 3/16 inch from these junctions. The Hastelloy cover did not weld to the Hastelloy liner.

A second experiment was conducted using the same welding parameters. The strip of Hastelloy positioned on the internal-support-die surface upstream from the Hastelloy liner did not help in welding the end cover to this narrow liner. The same distribution of Hastelloy X to 304 SS welds was noted in this specimen as for the previous specimen, with nonwelded areas located on the downstream side of all junctions.

The third and last experiment was conducted using a 3/16-inch standoff gap and a 1/2-inch layer of explosive. This time the steel tooling surfaces were covered with 304 SS foil and a strip of Hastelloy X again was positioned upstream from the narrow Hastelloy X strip representing the liner. This procedure did not eliminate the disrupting effect of the junctions, but prevented material from the tooling surfaces from being carried into the Hastelloy X-304 SS interface. Once again the Hastelloy X end cover and liner did not weld. Except for the junction effects which were less than in the previous experiments, good welds were produced between the Hastelloy X cover and the 304 SS plenum.

The results of these experiments indicate that the welding parameters used should be adequate for welding 3/16-inch Hastelloy X end covers to the plenum sections of the spoolpieces. The presence of junctions on the plenum surface will affect welding for some distance downstream. This contamination can be prevented by cladding the steel tooling surfaces with 304 SS foil prior to welding.

There is little possibility that the 3/16-inch Hastelloy X end covers will weld to the end surfaces of the Hastelloy X liner. It was concluded that it may be advantageous to consider welding the end covers prior to welding the liner, as there is a much better chance that the thin liner would weld to the end cover in this situation. If the end cover-liner joint could be successfully made in the spoolpieces by explosive-welding means, it would be possible to fusion weld it later to make this a leaktight joint.

SPOOLPIECE FABRICATION

The technology developed for the three explosive-welding operations was applied in the fabrication of two cylindrical spoolpieces. The sections which follow describe the step-by-step processing of these spoolpieces which have been designated as 1 and 2. It will become evident that different approaches were used in fabricating the spoolpieces. The approach used for Spoolpiece 1 was selected for convenience and to eliminate several processing steps without affecting the explosive-welding operations. The same approach was not considered for Spoolpiece 2 because of the thin wall thickness and the age-hardened condition specified for the Alloy 218 shell component. Another factor was the prohibitive cost of procuring a heavy-wall Alloy 718 forging. Spoolpiece 1 was fabricated as originally planned with a few exceptions, but problems encountered early in the fabrication sequence prevented Spoolpiece 2 from being completed. A sample from a previous 360-degree-segment experiment was evaluated in its place.

Spoolpiece 1 – Type 304 SS

Fabrication of Shell and Plenum

For convenience, the shell and plenum sections of Spoolpiece 1 were carried through the fabrication sequence as an integral unit, a thick-wall 304 SS forging. This approach was used in lieu of fabricating the shell and plenum components separately and then joining them. This forging, which measured 18 inches in OD by 10.5 inches in ID by 15 inches high, in addition to being the body of the spoolpiece, also served to contain the explosive forces of welding ribs, liner, and end covers to the spoolpiece. The forging itself was supported by an external 4340 steel forging measuring 26 inches in OD, 16 inches in ID, and 17 inches high. After machining both forgings to create an interference fit, the larger 4340 forging was expanded by heating and shrunk-fit onto the 304 SS forging.

Welding of Ribs to Shell

The inside surface of the 304 SS shell was machined to a diameter of 10.991 inches for the rib-welding step. A tooling cylinder was machined from hot-roll seamless steel pipe to nominal dimensions of 10.616 inches in OD by 10.241 inches in ID by 18 inches high. The cylinder was slotted on its outside surface with 120 equally spaced grooves oriented parallel with the cylinder axis. The grooves were machined to hold 304 SS ribs, nominally 0.04 by 0.125 by 18 inches, firmly in place so that the ribs extended out from the tooling surface about 0.01 inch.

The ribs were fitted into the tooling-cylinder grooves and this assembly positioned inside of and concentric with the shell forging, creating a nominal 3/16-inch standoff gap between the ribs and shell. The cylinder and ribs extended 2 inches above and 1 inch below the shell forging. A solid center mandrel of Zerolite was machined and similarly positioned inside of, and concentric with, the tooling cylinder, creating a nominal 23/32-inch annular gap between the two which was filled with SWP-1 granular explosive. This explosive loading had produced satisfactory rib-shell welds in several preliminary experiments. The same circular line-wave detonation scheme described in the earlier experiments was used to detonate the annular explosive charge simultaneously over its entire top surface. Figure 25 shows Spoolpiece 1 at this point as it was set up for this rib-to-welding step.

Once the ribs had been welded to the shell, it was necessary to cut the external 4340 steel forging away from the 304 SS shell forging to prepare it for further processing. From this point on, this steel forging was used as a split die, with high-strength steel bolts being used to hold its 180-degree halves together.

Welding of End Covers to Plenum

It was decided that the Hastelloy end covers should be welded to the spoolpiece plenum sections before the thin Hastelloy liner was welded to the ribs. This decision was based on the inability to weld the relatively thick end cover to the narrow end surface of the liner in the preliminary experiments. The possibility of welding the 0.02-inch-thick liner to the inside surface of the 3/16-inch-thick end cover is considered much better. In the event that good liner-end cover welds were not obtained when welding the liner to the ribs, the liner and end-cover components would be in a better position for fusion welding if the end covers were already welded to the plenum.

The 304 SS shell forging with the ribs and tooling welded to its inside surface was machined to prepare it for the end-cover welding operations. First, the back or inside surface of the steel tooling cylinder was machined, just enough material being taken off to make this surface concentric. A 1-inch-high ring section was cut from one end of the shell forging and the steel tooling leached away. Peel tests were made on this ring to determine the rib-shell weld integrity at this axial position along the shell length. The welds were found to be satisfactory so this plane was established as one plenum surface for the chamber. The channel configuration specified in NASA-Lewis Drawing No. CD62119, Amendment A, was then machined in this plenum surface. Figure 26 shows Spoolpiece 1 at this stage of processing.

The next step in preparing for the end-cover welding step was to fabricate the steel support tooling for the plenum channels. The earlier development studies had

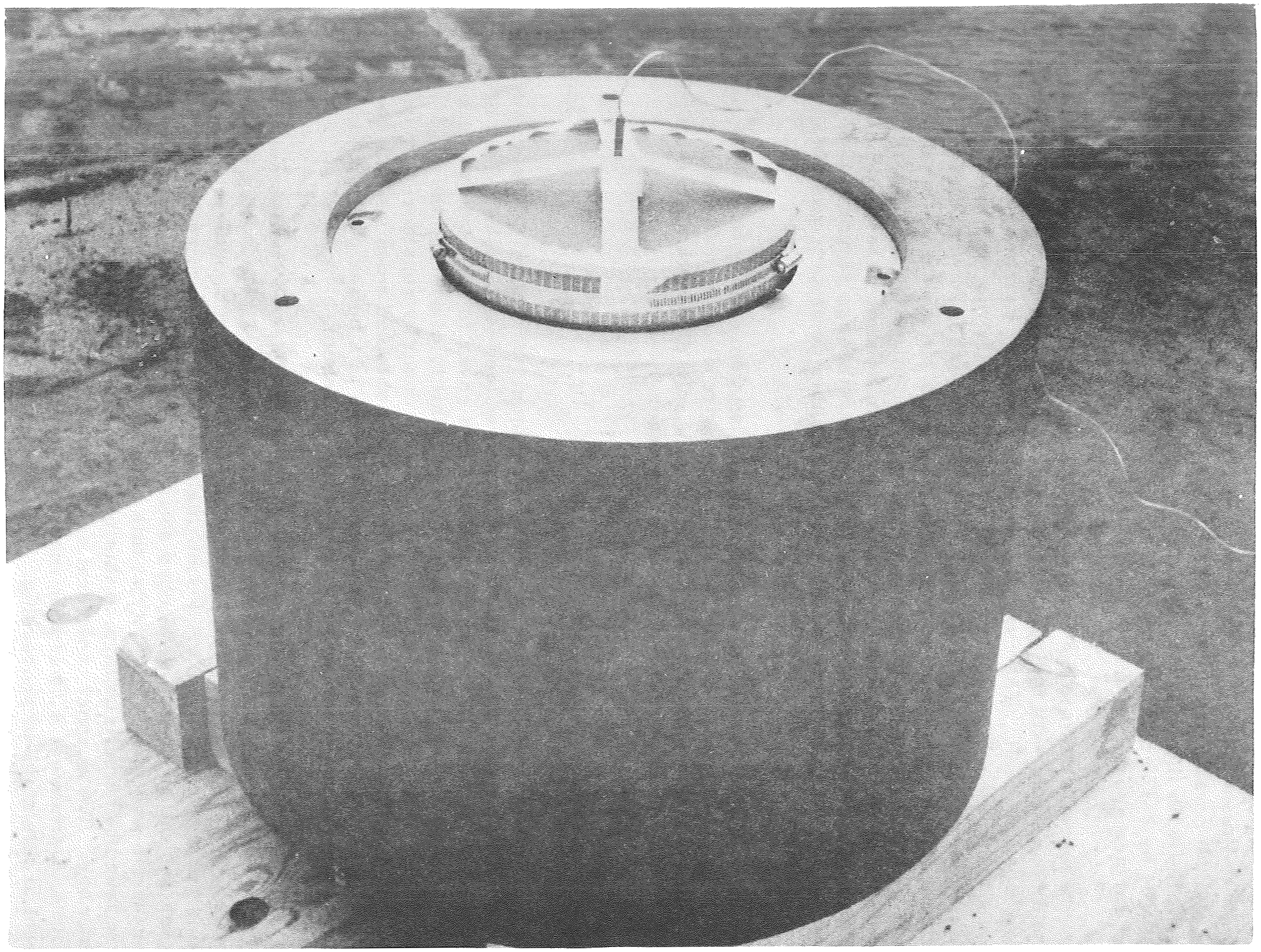
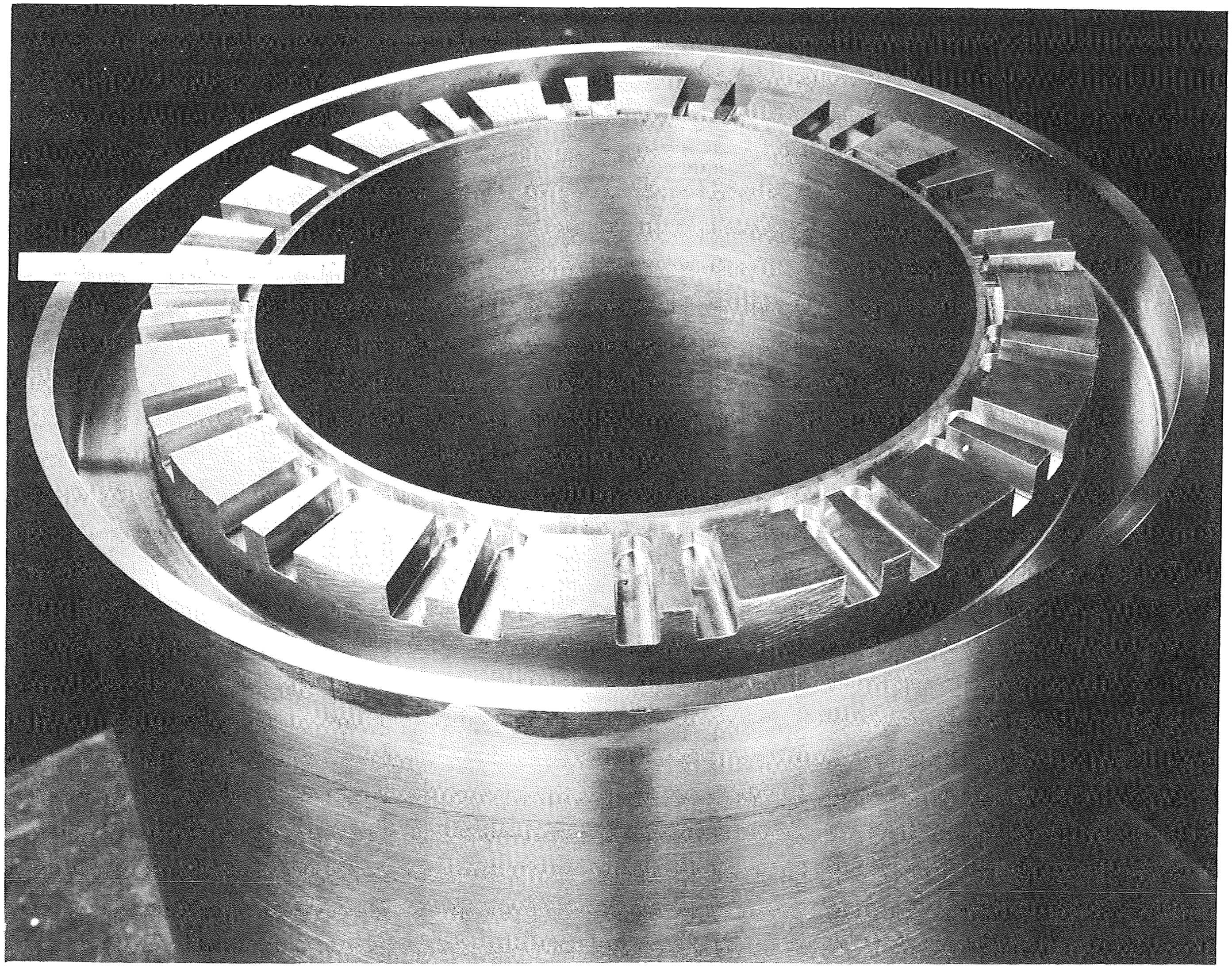


FIGURE 25. SPOOLPIECE 1 SETUP: FOR WELDING RIBS TO SHELL FORGING

Seen are the rib and tooling segment, the line-wave detonator for detonating the explosive charge, and the external support die.



~ 1/2 X

FIGURE 26. PARTIALLY COMPLETED SPOOLPIECE 1

At this point the ribs and tooling had been welded in place and
the channel configuration machined into one of the plenum end surfaces.

indicated the need for cladding the tooling surfaces with stainless steel to prevent steel from being swept into adjacent end cover-to-plenum welds downstream. A 20 by 20 by 1.5-inch-thick plate of mild steel was explosively clad with 0.010-inch-thick 304 SS. The tooling pieces required to fill the plenum channels were machined from this clad plate.

In assembling the various components for the end-cover welding step, the arrangement shown earlier in Figure 23 was used. A 4340 steel cylinder was machined to fit inside the machined surface of the shell forging. The split die used as an integral die in the earlier rib-welding step was machined and bolted around the outside of the shell forging. These inside and outside dies gave support to the edges of the spoolpiece plenum during welding of the end cover. Thin protective pieces of stainless steel were put on the top surfaces of the dies to prevent the end cover from welding to them. The dies were adjusted vertically so that the protective surfaces of the dies were flush with the clad tooling and plenum surfaces of the chamber. A 3/16-inch-thick disk of Hastelloy X was supported 3/16 inch above the plenum surface and parallel with it. A 5/8-inch-thick layer of SWP-1 explosive was placed in contact with the Hastelloy. Using a central detonation scheme, the end cover was welded to the spoolpiece plenum surface.

Close examination revealed several areas where the end cover did not weld to the outer plenum surface at a point beyond the circumferential tooling channel. These areas of nonweld were attributed to the outer tooling – plenum junction. It was decided to machine off the end cover and prepare the plenum surface for a second attempt to weld the end cover. This time a 0.02-inch-thick layer of Hastelloy was first welded to the plenum surface. As expected, the disrupting effects of the tooling-plenum junctions were much less for this thinner layer and good welds were achieved in all areas. A second layer of 3/16-inch Hastelloy was next welded over the thinner layer whose surface was continuous and free from junctions. A good Hastelloy self-weld was achieved in all areas.

The end cover was machined to final thickness so that the other spoolpiece plenum surface could be established by measurement. After it was verified that the rib-to-shell welds were good at the location of the second end cover, this surface was prepared for welding the second end cover. The same procedures were used for preparing and assembling the various components for this welding step as were used previously. Once again a two-stage welding sequence was used with 0.02-inch-thick Hastelloy layer being welded first, followed by the 3/16-inch-thick end cover. Good welds resulted from both operations. The end cover was then machined to final thickness.

Welding of Liner to Ribs

In preparing the 304 SS shell forging for the liner-welding step, the inside surface was machined so as to fully expose the rib surfaces in all areas. During this machining step, the ribs were exposed first in the center portion of the chamber. It was necessary to machine another 0.04 inch to expose the rib surfaces out to the ends of the chamber. Since the original height of the ribs was 1/8 inch, the rib height in the center of the chamber was about 0.085 inch and that towards the chamber ends was about 0.120 inch. This machined surface then was treated with acid to reduce the tooling from 0.005 to 0.010 inch below the rib surfaces.

Composite cylinders of Hastelloy and steel were fabricated by rolling 0.02-inch Hastelloy and 1/16-inch steel sheet into cylinders and fusion welding their longitudinal seams. Electron-beam welding was used to make these cylinders to closely controlled sizes, with the Hastelloy cylinder just fitting over the steel cylinder. This combination was explosively sized in a die to force the cylinders into intimate contact and to produce a composite cylinder with a specific diameter.

The 15-inch-high composite cylinder was positioned inside the spoolpiece, forming a nominal 1/16-inch gap between the Hastelloy and the ribs. A solid cylinder of Zerolite was located inside the composite cylinder, and formed a 7/16-inch annular gap between them. Both the composite cylinder and the Zerolite plug extended 2 inches above and 1 inch below the ribs. The 7/16-inch gap was loaded with SWP-1 explosive, and this charge was detonated using the same circular line-wave detonation used in earlier experiments.

The Hastelloy liner appeared welded to the ribs in all areas, but there were a few areas at both ends of the chamber where the liner-to-end cover weld was poor. Fusion-welding techniques were used to patch the nonwelded areas, and leaktight joints were produced at these locations.

Removal of Support Tooling

The spoolpiece at this stage of fabrication had its ribs, liner, and end covers welded into place. The next step in the processing sequence was to remove the steel support tooling between the ribs and in the plenum sections. It was first necessary to drill six holes into both plenum sections to gain access to the tooling. Inlet and outlet tubes will later be fusion welded in these holes to supply a flow of coolent to the spoolpiece. The spoolpiece was immersed in a tank containing a 50 percent nitric acid solution maintained at 180 to 190 F.

It was a relatively easy matter to dissolve the tooling from the plenum sections of the spoolpiece because of the easy access to these areas. However, a much longer period of time was required to remove the tooling from the channels because of their small cross-sectional area and the limited access to them, which caused difficulties in keeping fresh solution in the channel holes. A significant increase in leaching rate was obtained by using bottom heaters to naturally stir the leaching solution and frequently turning the spoolpiece end-for-end, or laying it on its side. The leaching progress was monitored by a magnet which was placed against the thin Hastelloy liner to detect the steel tooling beneath. This method had proven to be a very sensitive means of detecting even small amounts of steel in earlier control samples.

Finish Processing and Proof Testing

When all of the steel support tooling had been removed from the spoolpiece, several fusion welding and machining steps were completed to prepare it for proof testing and for test firing at NASA-Lewis. The end-cover welds with the liner and with the plenum surfaces on the outer edges of the spoolpiece were not complete in all areas after the end covers and liner had been explosively welded in place. All of these junctions were fusion welded to insure that they were leaktight.

The spoolpiece was then machined to reduce the shell section thickness to its final dimension, and O-ring grooves and a series of bolt holes through the plenum sections were machined in both end-cover surfaces.

Six 304 SS pipes, 8 inches long, were welded into the holes already drilled into each plenum section. A flow check was made on the spoolpiece by circulating water through different combinations of these inlet-outlet tubes, some of which were closed off. This check showed that all sections of the spoolpiece were open. All but one of the tubes were then closed off for proof testing the spoolpiece. First, it was pressurized with 50 psi of helium gas with the spoolpiece submerged in water. One or two very small leaks were found at the end cover-to-liner junction. These welds were reworked and showed no further leakage when subjected to the helium pressure a second time. The spoolpiece then was pressurized with water to 750 psi. No leakage of water was found in any areas.

Figure 27 shows the completed Spoolpiece 1 after proof testing. It was shipped to NASA-Lewis in this condition.

Spoolpiece 2 – Alloy 718

A different approach was used to fabricate Spoolpiece 2. In contrast to Spoolpiece 1, the shell and plenum sections of Spoolpiece 2 were made separately and later joined. This procedure was necessitated by the thinner wall and age-hardened treatment specified for the Alloy 718 shell. The cost of procuring a heavy-wall forging of Alloy 718 to process the shell and plenum as an integral unit, as was done for Spoolpiece 1, was prohibitive.

Fabrication of Shell and Plenum

Two Alloy 718 shells were made, as one was damaged when a power failure occurred as its longitudinal seam was being welded. Cracks which formed in the weld zone could not be repaired. The second shell was made successfully by rolling 0.109-inch-thick sheet into a cylinder and welding its longitudinal seam by automated TIG techniques. Plenum sections were machined from two Alloy 718 ring forgings; these sections were left oversize and had flanges which aligned with the cylindrical shell, Figure 28. Automatic TIG welding was used to make the girth welds joining the plenum sections to the shell. These welding steps caused the shell-plenum assembly to warp considerably.

The as-welded shell-plenum assembly was explosively formed in a split die to eliminate the warpage and size the assembly. Two forming steps were required to accomplish this using centrally located line charges and water as an energy-transfer medium. After forming, it was necessary to add more filler metal to both girth welds so that the inside surface of the shell would be smooth when it was machined. This welding step resulted in additional warpage which was concentrated in the girth-weld areas. A second but different kind of forming procedure was performed on the shell-plenum assembly after it was solution treated at 1950 F for 1 hr and water quenched. A solid mandrel of mild steel was positioned inside the assembly. A 1-inch-wide strip of plastic-explosive sheet, Detasheet*, was placed on a 1/4-inch-thick layer of rubber,

*Product of E. I. du Pont de Nemours & Company.

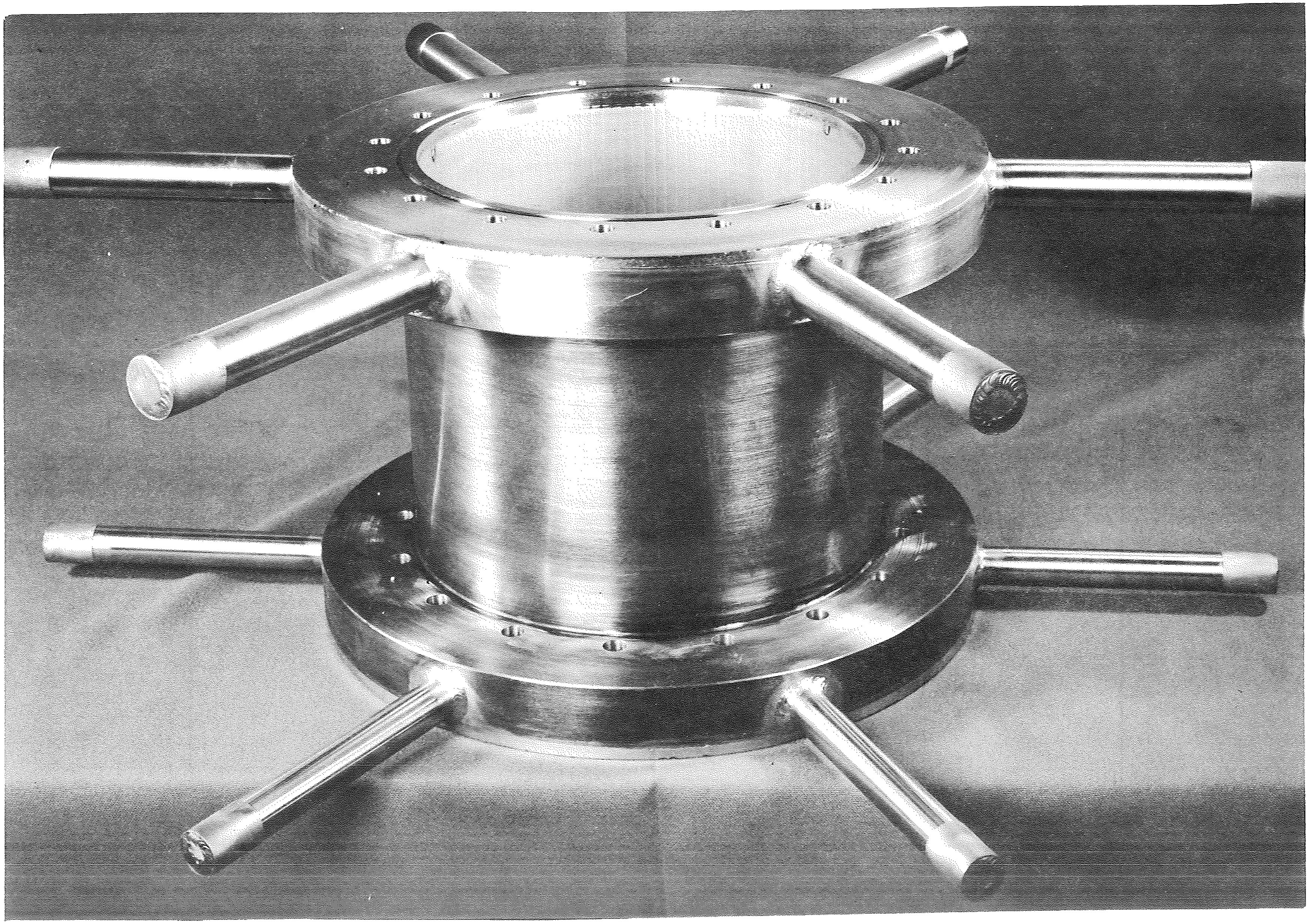


FIGURE 27. COMPLETED SPOOLPIECE 1

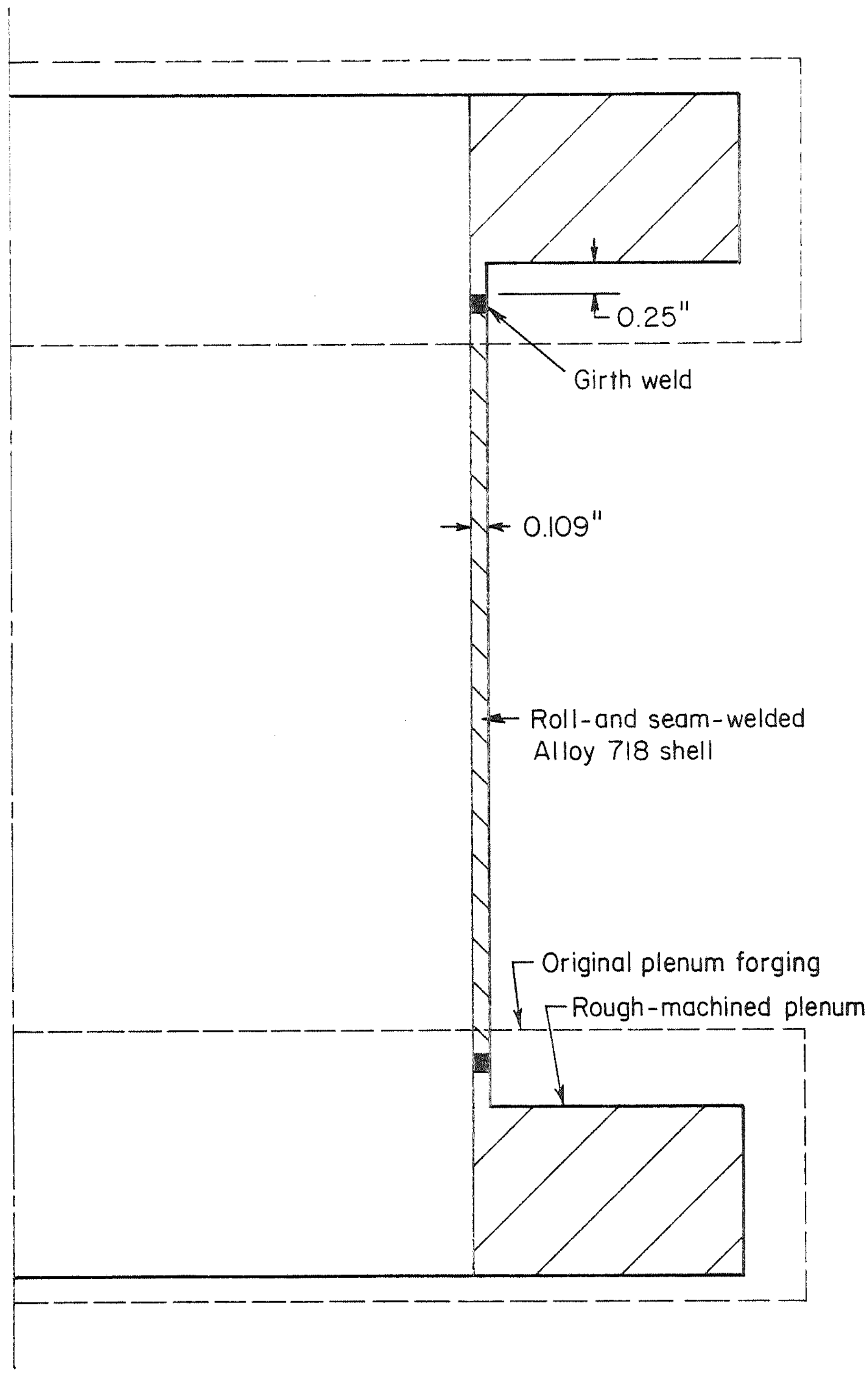


FIGURE 28. DIAGRAM OF TECHNIQUE USED FOR FABRICATING SHELL AND PLENUM STRUCTURE FOR SPOOLPIECE 2

which was in contact with the girth weld on the outside surface. Detonation of this charge forced the assembly against the steel mandrel, thus ironing out the warpage in this area. This forming procedure was repeated on the other girth weld, producing an assembly which was within 0.005 inch of being round. The shell-plenum assembly then was aged to fully harden it.

Welding of Ribs to Shell

The shell-plenum assembly was supported by external dies as ribs and tooling were explosively welded to the shell inside surface. First, split rings, machined from a 4340 steel forging, were positioned around the shell and between the plenum sections, forming a composite cylinder of uniform diameter. The split die previously used in the fabrication of Spoolpiece 1 was clamped around the composite cylinder and held firmly in place by high-strength steel bolts. Alloy 718 ribs were machined from 0.04-inch-thick sheet stock and a grooved tooling cylinder was machined from hot-roll steel pipe in the same manner as previously described for Spoolpiece 1. The cylinder diameter was selected to give a nominal 3/16-inch standoff gap with the shell inside surface when the cylinder was positioned inside the shell.

The assembly procedures and welding parameters used to weld the ribs to the age-hardened Alloy 718 shell were the same as those described earlier for Spoolpiece 1. Using a circular detonation arrangement as before, a 7/16-inch layer of SWP-1 explosive was detonated, accelerating the tooling cylinder and ribs to collide against the shell surface.

This welding step severely damaged the spoolpiece shell as the split die supporting it was thrown aside when its bolts ruptured. The damage was in the form of localized distortion and cracks, the cracks being both longitudinal and circumferential. The longitudinal cracks were in or near the weld seam, while the one circumferential crack was located at the junction between one plenum section and the shell, but not in the girth-weld seam. The shell damage was sufficient to prevent it from being repaired. As a result it was not possible to complete fabrication of Spoolpiece 2.

Since the 360-degree Alloy 718/Hastelloy X segment welded in the initial part of this task was essentially a spoolpiece without the plenum sections, it was decided that it should be proof tested in place of the failed Spoolpiece 2. The ends of the channels of the segment were mechanically sealed and it was helium leak checked at 50 psi and hydrostatically proof tested with water at 750 psi with no indication of any defects or unbonded areas. Following proof testing, the segment was forwarded to NASA-Lewis for further evaluation.

SUMMARY OF RESULTS

The results of this task have shown that cylindrical-channeled structures can be fabricated by the explosive-welding process. In addition, end-cover plates can be explosively welded over the complex channeling of the manifold section.

It was found in the initial studies on the task that greater explosive loadings and/or initial standoff gaps were required to explosively weld the ribs to the shell structure in the cylindrical configuration than were required in the flat-panel structures. The parameters required for welding the thinner liner to the ribs in the cylindrical configuration, however, were essentially the same as for the flat panels. Strong rib-to-shell and liner-to-rib welds were achieved in the cylindrical configuration for both the 304 stainless steel/Hastelloy X and Alloy 718/Hastelloy X systems.

The preliminary studies for explosively welding the Hastelloy X cover plates to the plenum section revealed several important facts:

(1) The mild-steel tooling in the manifold channels should be clad with a thin layer of stainless steel to prevent material from the tooling surfaces from being carried into the cover plate/plenum interface.

(2) The presence of junctions (between plenum and the tooling) in the interface will affect welding for some distance downstream from the junction, particularly when welding a thicker plate such as the 3/16-inch-thick Hastelloy X cover plate. It was found later in the actual fabrication of Spoolpiece 1 that a thin (0.020-inch) layer of Hastelloy X could initially be clad over the plenum surface with little or no junction effects, after which the cover plate could be welded to the surface of the thin layer, again with minimal junction effects.

(3) It was found that the end cover plate could not be welded across the narrow end surface of the liner and that the liner should be welded after the end covers had been welded in place. This gave a better chance of obtaining a leaktight seal between the liner and the end cover.

Following the successful fabrication of Spoolpiece 1 (304 stainless steel/Hastelloy X), the acid-leaching removal of the steel tooling from the channels required a relatively long time. The leaching rate was increased by using bottom heaters to achieve natural convection stirring of the acid solution and periodically turning the spoolpiece. Following removal of the tooling, the spoolpiece passed the required proof testing.

Considerable difficulty was encountered in fabricating Spoolpiece 2 (Alloy 718/Hastelloy X). This difficulty was manifested initially by severe distortion of the Alloy 718 shell structure during its fabrication. This distortion was corrected by explosive forming. The shell structure then failed during the explosive welding of the ribs to it, showing that better external support would be required during the rib-welding operation. An Alloy 718/Hastelloy X spoolpiece segment was successfully proof tested in place of the actual spoolpiece.

TASK III. FABRICATION OF NOZZLE SEGMENTS

OBJECTIVE, APPROACH, AND COMPONENT DESCRIPTION

The objective of the Task III portion of this program was to demonstrate the feasibility of using explosive welding to fabricate a channelled rocket nozzle. For this feasibility demonstration, a presently used nozzle design (RL-10) was modified and chosen for study. It was not felt necessary to explosively weld a complete 360-degree nozzle, since welding just a segment of that nozzle would demonstrate the applicability of the process to the nozzle geometry. Segments such as the 60-degree one shown in Figure 29 were thus chosen as demonstration pieces.

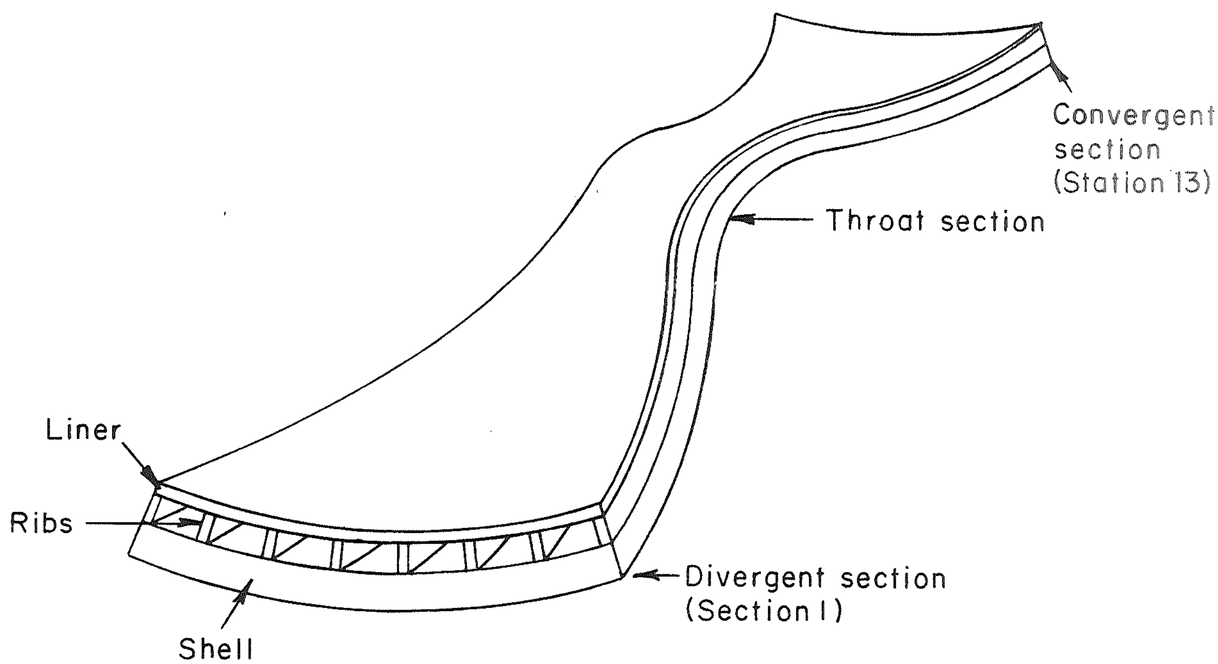


FIGURE 29. A TYPICAL NOZZLE SEGMENT

Total length of segment = 13.5 in.
Maximum ID (at end of divergent section) = 11.38 in.
Minimum ID (at throat) = 5.46 in.

The materials to be employed were selected on the basis of the results of the Task I effort. The two systems selected were:

A. Type 304 stainless steel shell and ribs with a Hastelloy X liner

B. Alloy 718 shell and ribs with a Hastelloy X liner.

Since the majority of the techniques and methods used to weld a nozzle would be identical for both material systems, it was decided to devote the major effort to developing the methods for fabricating a part from one of the materials combinations. This would then be utilized to fabricate a segment from the second materials combination. The materials combination chosen for the development work was combination A above – Type 304 stainless steel and Hastelloy X.

It was recognized that attempets to produce explosive welds between doubly curved components would be an extremely difficult task and would be extending considerably the state of the art of explosive welding. Therefore, the program was structured to approach the problem in a gradual manner – attempting to take a single step at a time and work from the relatively simple to the more complex.

Much past work has shown that the process of explosive welding can be accomplished quite easily between two flat plates, or between two cylinders when the weld is made in the axial direction. Note that in both of these configurations the surfaces to be welded are noncurved in the direction of welding. That is, welding (or detonating the explosive) axially presents a noncurved welding surface, while in a circumferential detonation, the welding surface is curved.

The first step in welding components of a nozzle configuration was to demonstrate that surfaces curved in the direction of welding can be welded. Then, provided that a reasonably sound weld could be produced in this configuration, the second step was to demonstrate the capability of welding to a doubly curved (i. e., axially and circumferentially curved) surface. Both of the components to be welded should be solid plates (i. e., no ribs would be used) so as to minimize the fabrication and assembly problems. The third step would then be to demonstrate welding using a ribbed component in the doubly curved nozzle configuration.

Component Fabrication

The components required during the course of this program were quite specialized and exhibited rather complex curvatures, as indicated in Figure 29. For example, sections of nozzle components having radius ratios of 2 to 1 were required. Consequently, conventional fabrication operations – rolling and welding, machining, etc. – could not be used, and most of the components had to be fabricated by nonstandard techniques. A considerable amount of the program effort was spent on this fabrication phase, and several technologically useful and novel fabrication methods were developed.

The major components required for the conduct of this explosive welding study are listed in Table 7. Note that in this table the component diameter (or equivalent) is given in terms of Y, which is the diameter of the nozzle at a given axial distance, X. These X and Y dimensions, together with other engineering details of the nozzle segments, are shown in Figure 30. The lengths of the nozzle components used in this welding study were increased to provide for the end losses characteristic of the explosive-welding process. One end was lengthened by 2 inches, while the opposite, more tapered, convergent section of the nozzle was lengthened by 2-1/2 inches. Thus, all components and tooling pieces were fabricated to a length of 18 inches, rather than the 13-1/2-inch length required of the finished nozzle.

TABLE 7. COMPONENTS REQUIRED FOR NOZZLE FABRICATION

Component	Material System	Material	ID in Terms of Y (Figure 30)	Number Required per 60-Degree Segment	Total Number Required for Program
Support die	A	4140 steel	Y + 0.50	1 (reusable)	5
Support die	B	4140 steel	Y + 0.23	1 (reusable)	5
Shell	A	304 stainless steel	Y + 0.14	1	8
Rib mock-up	A	304 stainless steel	Variable	1	4
Shell	B	Alloy 718	Y + 0.14	1	4
Rib mock-up	B	Alloy 718	Variable	1	2
Ribs - full length	A	304 stainless steel	(Variable)	11 for segments with discontinuous ribs	64
				21 for segments with only continuous ribs	
Ribs - discontinuous	A	304 stainless steel	Variable	10 (each end)	20 (each end)
Ribs - full length	B	Alloy 718	Variable	11 for segments with discontinuous ribs	22
Ribs - discontinuous	B	Alloy 718	Variable	10 (each end)	20 (each end)
Liner	A and B	Hastelloy X	Variable	1	8
Tooling supports for ribs	A and B	Mild steel	Variable	1 set	7

Support Dies

Support dies were required for each nozzle-welding experiment, and were used to support the shell during the two welding steps performed on it (the rib-to-shell and liner-to-rib welding operations). The dies were solid, hardened 4140 steel and had a minimum thickness of 1-1/2 inch.

Two dies were fabricated – one for each of the two materials systems. The outside diameters of the shells for the two systems were slightly different because of different shell thicknesses; consequently, two different size dies were required. The dies were rough machined from cylindrical (15-1/4-inch OD by 5-1/2-inch ID by 18 inches long) steel forgings on a tracer lathe. After being heat treated, they were final machined and longitudinally cut into three sections, one of which was a 72-degree segment, while the other two were 144-degree segments. The 72-degree segment was used for the early welding experiments, while the other segments of each die were held in reserve in case of damage or other changes to the segment being used.

As the program progressed, and as various component fabrication options were abandoned, a need developed for dies for explosive forming. The segments of the support dies, which had initially been procured and fabricated for use in the welding study, were found to be ideally suited for this use as well. Consequently, both the full die and/ or individual die segments were used extensively during forming of several of the nozzle components.

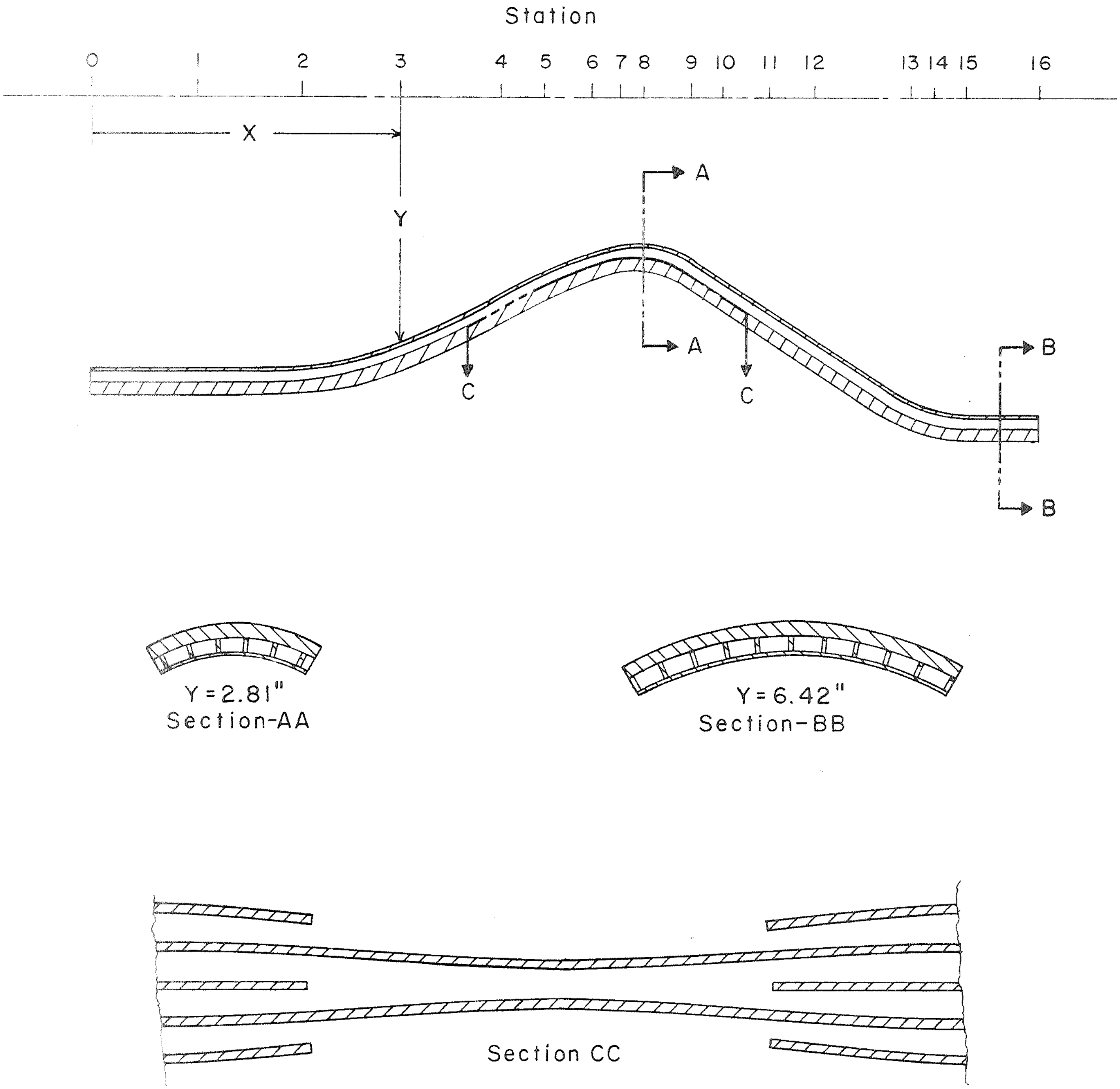


FIGURE 30. DETAILS OF NOZZLE SEGMENT

Stainless Steel Shells

The shell components are the thick structural elements which provide the main strength to the nozzle. For this program, they were the elements to which the rib mock-ups were welded in the preliminary experiments and to which the ribs were welded in the final demonstration experiments. The maximum outside diameter of the extended-length shell (at the convergent end of the nozzle) was 12.84 inches, and the minimum outside diameter (at the throat section) was 6.42 inches. The shell wall was 0.360 inch thick, and the total component length was 18 inches.

A number of potential methods of fabricating these shells were examined; it was decided that machining and sectioning of a complete nozzle would be the most practical means to produce the required sections. However, a blank for machining was required. Two types of "raw material" were considered – hollow forgings or formed-to-shape tubular components of the required thickness. Forgings were eliminated from consideration when the quoted prices and delivery times were found to be unreasonable.

Explosive forming was the method chosen to fabricate the nozzle blanks. Controlled expansion of the ends of a commercial-grade, thick-walled stainless steel pipe was the method used to produce nozzle-shaped components, which then were final machined into finished shells.

Two complete blanks were fabricated by this method. Two lengths of commercial-grade, nominal 6-inch-diameter, double-extra-heavy-wall pipe (6.518-inch OD by 7/8-inch-thick walls) were used to form the nozzles. The initial wall thickness was calculated to provide the required thickness of material after forming at the maximum point of expansion (using a simple conservation of mass equation). Each tube was explosively expanded without the use of a die in several series of controlled expansions, using axially placed charges extending partially into the pipe, as shown in Figure 31. The tubes were expanded about 30 percent in several separate expansion operations, annealed, and then subjected to another form-anneal cycle. The final forming operation on each tube was done in a die (the die fabricated for use in the welding experiments), whereas the other operations were all free formed – i.e., no die was used. Twenty expansions per tube were used, and they caused the tube to expand, in a controlled manner, to greater than twice its original diameter. The tube, after final forming, was given a final anneal, machined on a tracer lathe, and sectioned longitudinally into 72-degree segments.

The explosive charges used in the expansion experiments consisted of lengths of glass tubing filled with Trojan SWP-1 dynamite. The diameters, lengths, and positioning of the charges were varied during the course of the complete forming cycle. Charges were either 25 or 28-mm in OD and ranged in length from 9 to 14 inches. These variations were incorporated to attain the desired formed contour. In the early expansion operation, the longer charges were employed; as the center sections were formed to the required size, shorter charges were used. To prevent fracture of the tube during each forming operation, the explosive charge was calculated such that the radial expansion velocity imparted to the tube was well below that required to cause fracture. In addition to this precaution, the tube was annealed at 1900 F for 1 hour after each approximate 30 percent expansion.

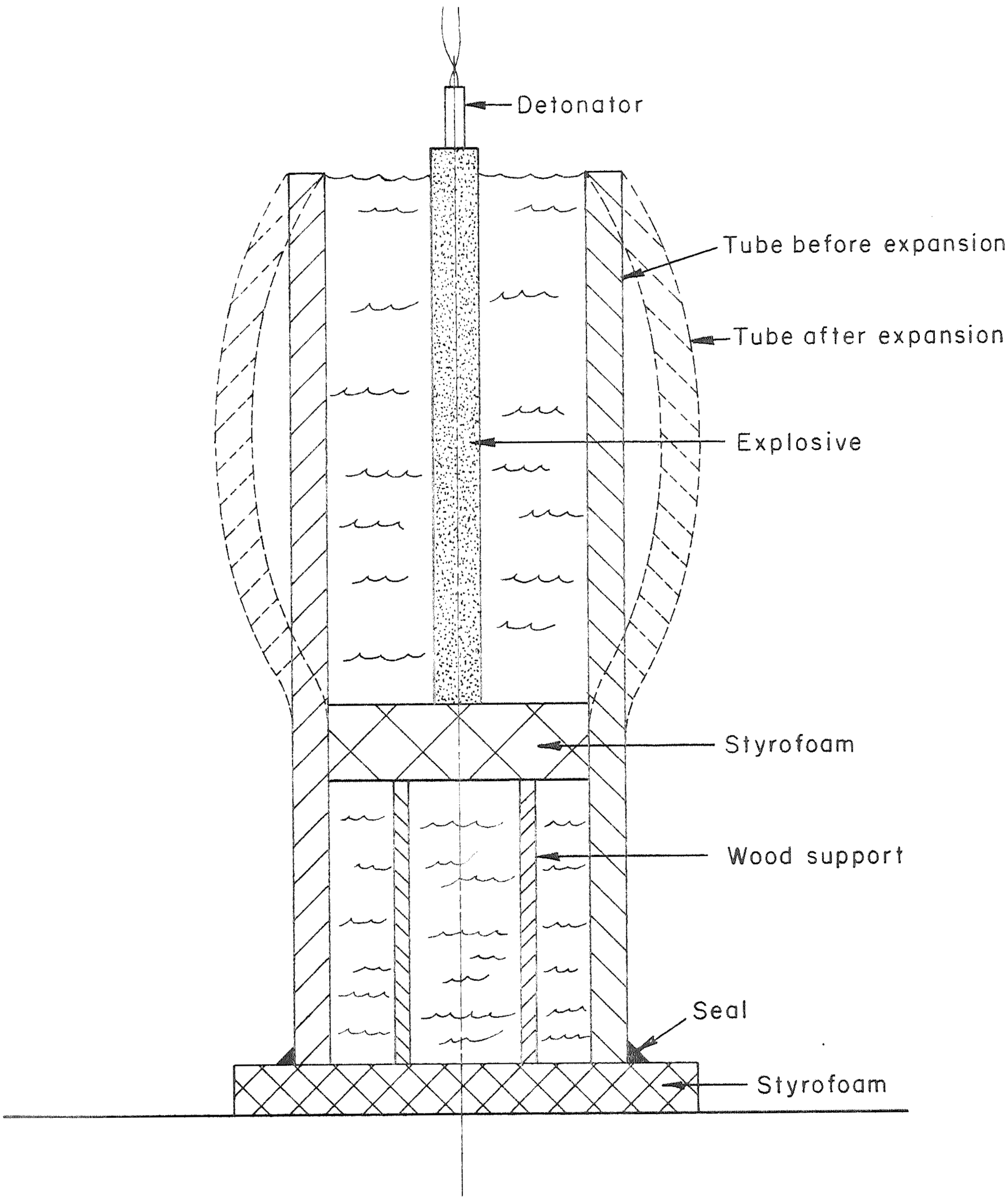


FIGURE 31. SETUP FOR EXPLOSIVE FREE FORMING OF TUBES

The details of the expansion operation are shown in Figure 31. The tube was positioned on a Styrofoam block and the junction between the tube and block was sealed with modeling clay. The charge, contained in a glass tube and sealed on both ends, and its wood-and-Styrofoam support were then positioned in the tube. The stainless tube was filled with water, the detonator was attached, and the charge was detonated. The tube was bulged by this operation, and as the figure shows, was bulged the maximum amount at the midpoint of the charge. As expected, it did not expand as much at each end as it did in the center. This effect aided considerably in forming the nozzle and is due to (1) the loss of forming pressure caused by venting of the water at the ends and (2) the restraints imposed by the geometry and material strength of the adjacent unexpanded sections.

The forming operation was repeated on one end of the tube until an approximate 30 percent expansion had been achieved (usually three or four expansions). The tube then was inverted, and the other end was expanded similarly to about 30 percent strain. The tube was then annealed and expanded further.

The progressive expansion of one of those tubes is shown graphically in Figure 32. Photographs showing several stages of the expansion of a shell tube and a mock-up tube (described in the next section) are presented in Figures 33 and 34.

For both of the shell tubes, the final free-forming operation expanded a portion of the tube to a diameter slightly greater than the inside diameter of the die, thus preventing the tube from being positioned in the closed die. It was therefore necessary to reduce the diameter at these overexpanded points. For one of the tubes, the overexpansion was very slight, and it was possible to machine the excess material from the OD of the tube and still leave sufficient material to provide a full-thickness piece. For the other tube, however, the enlarged section was considerably oversize, and it was not possible to machine the excess without thinning the wall excessively. The overexpanded section was therefore reduced in diameter through use of a small external charge of plastic-sheet explosive, the same as was used on the shell structure in Spoolpiece 2. This charge (3 $g/in.^2$ of Detasheet) was placed over the overexpanded sections, with several layers of foam rubber interspersed to prevent spallation of the tube, and detonated. The impulse imparted to the tube reduced the diameter at the desired points, and allowed the tube to be placed in the die and expanded to its final form.

The fully formed tubes were then given a final anneal and machined to the required dimensions on a tracer lathe. One of these fully machined nozzles is shown in Figure 35. The machined nozzles were sectioned longitudinally into 72-degree segments and used in the welding experiments.

Stainless Steel Rib Mock-Up

The rib mock-ups were used as stand-ins for the rib-and-tooling assembly during welding experiments in which the welding behavior of a double-curved shape (a nozzle) was examined. They were fabricated from solid stainless steel, were 0.180 inch thick, and were curved to match the shell components.

Two methods were employed in the course of fabricating these components; both of them employed explosive forming. The first of these methods involved the expansion of pipe (similar to the shell-forming operation), whereas in the second, flat sheets were

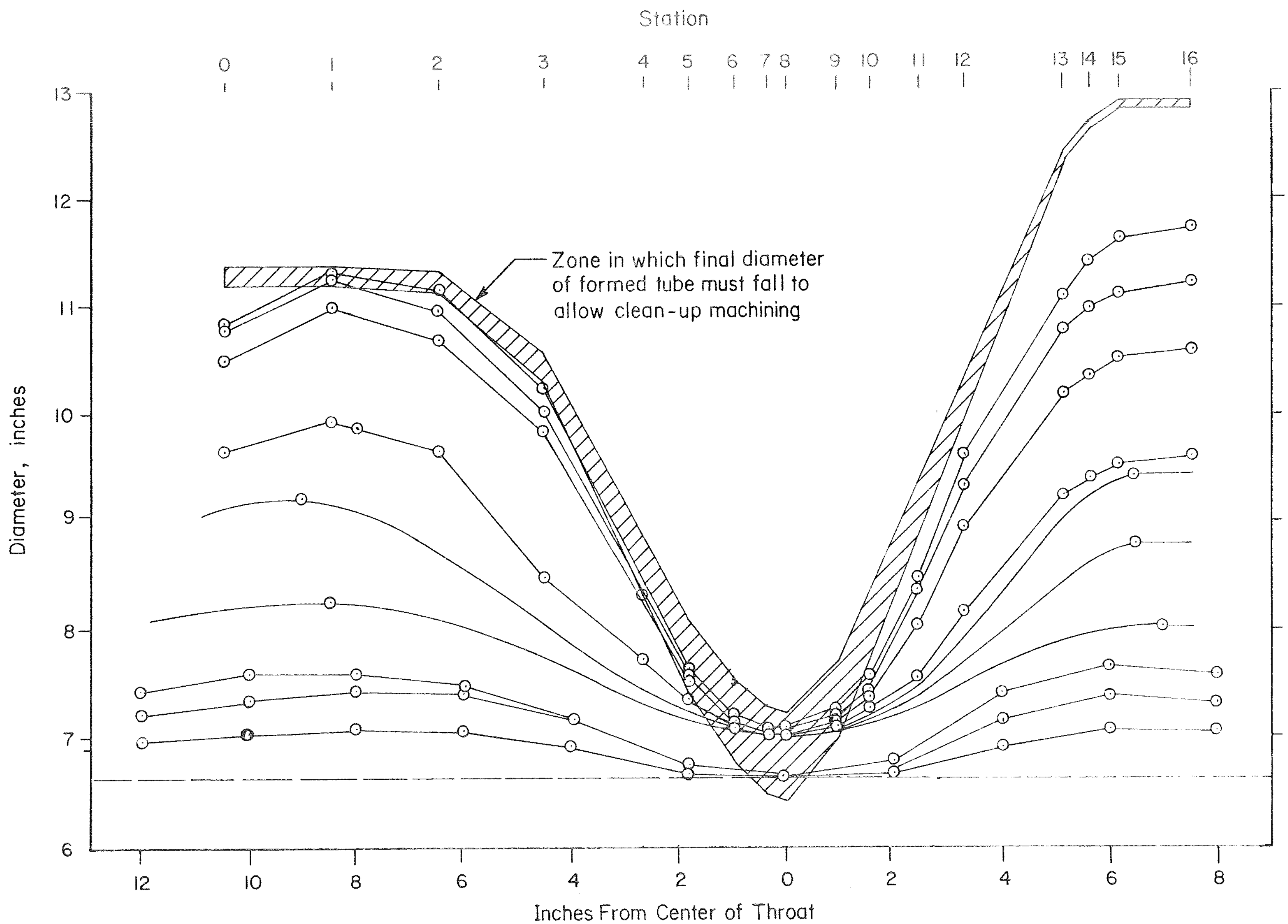


FIGURE 32. GRAPHIC PLOT OF PROGRESSIVE EXPLOSIVE EXPANSION OF HEAVY-WALLED STAINLESS STEEL PIPE

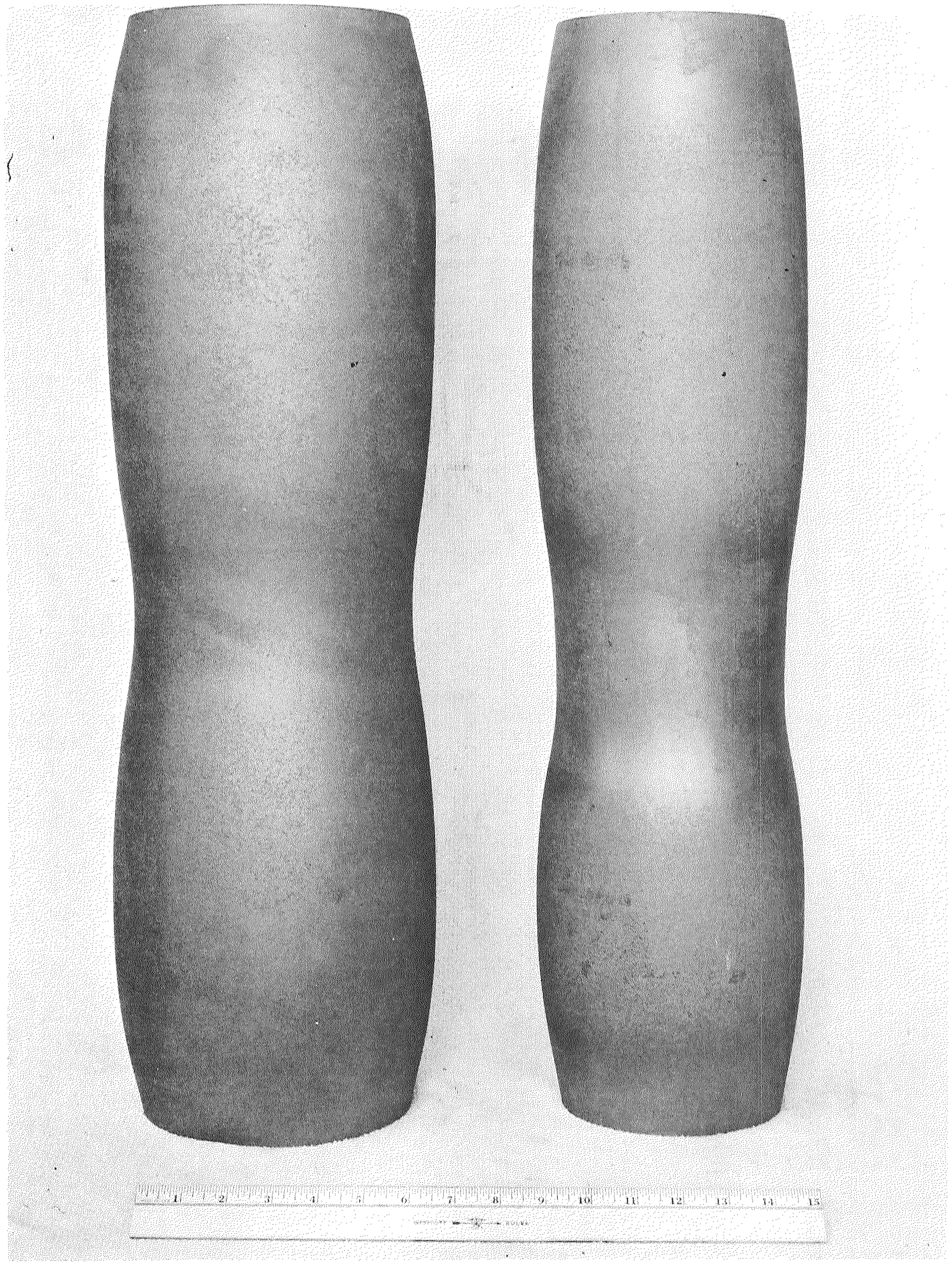


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FIGURE 33. STAINLESS STEEL TUBES AFTER FIRST FORMING CYCLE

The tube on the left is to be used for shells; the tube on the right is for rib mock-ups.

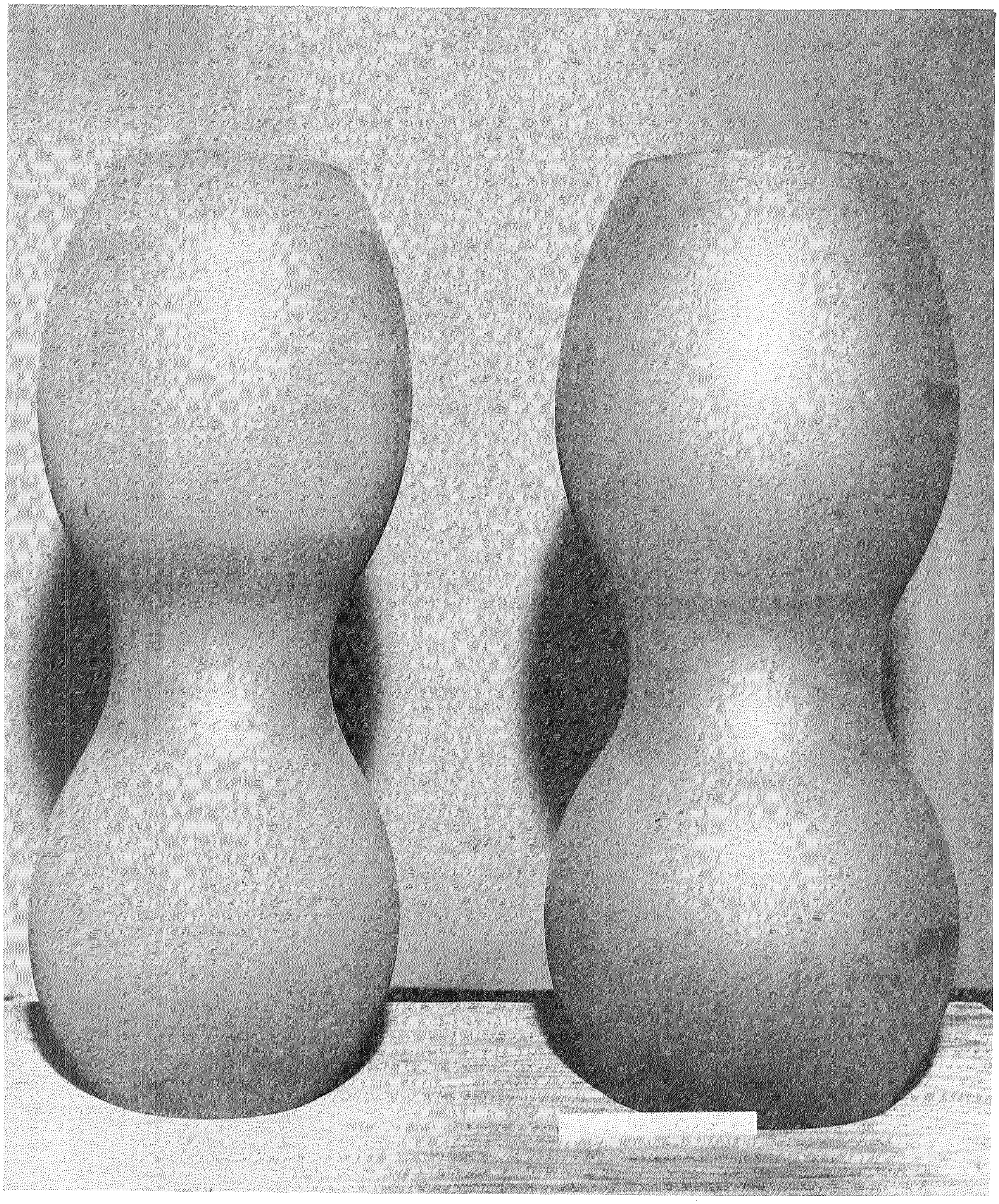

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FIGURE 34. STAINLESS STEEL TUBES AFTER THREE FORMING CYCLES

The tube on the left is to be used for rib mock-ups; the tube on the right is to be used for shells.

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FIGURE 35. EXPLOSIVELY FORMED AND FINAL-MACHINED 304 SS NOZZLE SHELL

formed into a female die. In the course of fabricating these components, and for reasons presented below, both of the methods were used.

The pipe-expansion work was carried on simultaneously with the expansion of the shell-component pipes. The starting material for the rib mock-ups consisted of two 28-inch lengths of nominal 5-inch, Schedule 120 (5-9/16-inch diameter, 1/2-inch wall thickness) stainless steel pipe. These pipes were expanded using the same operations and precautions employed in the shell-pipe expansions. Partially expanded pipes are shown in Figures 33 and 34.

The pipes were expanded to about two-thids of the final size required. At that point, and because of other program considerations, work was suspended on the partially expanded pipes, and an alternative method was used to fabricate the required components. By this method, which was developed and used in a concurrent effort to fabricate Alloy 718 shells, flat sheets of material were formed, in a single operation, into a 72-degree segment of die.

The decision of change the method of fabrication was based on considerations of time and cost. This new flat-plate explosive-forming process had been developed for use with the Alloy 718 and Hastelloy X components and had been shown to be both simple and rapid; consequently, its use would conservably accelerate the program performance.

The component arrangement for the flat-plate forming operation is shown in Figure 36. Briefly, the equipment consisted of a 72-degree die segment, a sheet of the metal to be formed, a cylindrical charge positioned several inches from the plate and oriented with its axis parallel to the die's axis, and a large watertight box. The plate was suspended a small distance above the die and the water required for forming was in a wooden box which had been lined with a sheet of polyethylene plastic.

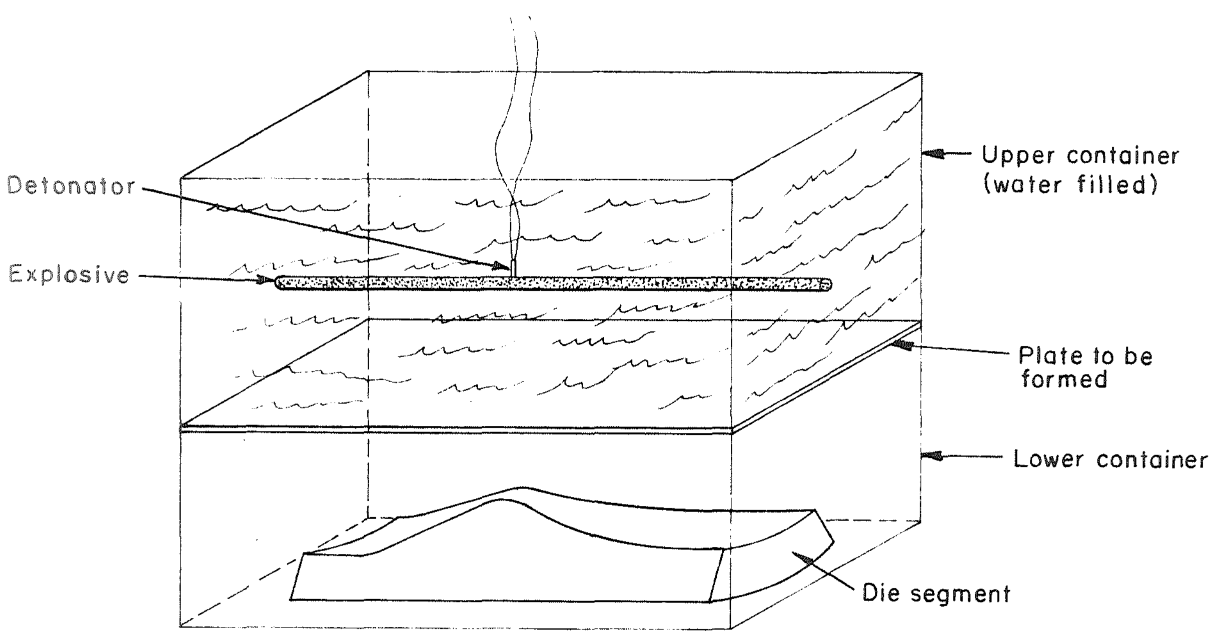

FIGURE 36. SETUP EMPLOYED FOR FLAT-PLATE FORMING OPERATION

In a typical forming operation, the die segment was set on a level section of ground and a 12-inch-high wooden frame, slightly larger than the die, was positioned around it. This frame contained on its inside surface a set of pegs which supported the plate to be formed at a height several inches above the die surface. A 3/16-inch-thick stainless steel plate was placed on the pegs, and a second 12-inch-high wooden frame was placed atop the first. A polyethylene-sheet bag was positioned inside the rectangular cavity formed by the duplex frame and the steel plate. The explosive charge, contained inside a 24-inch-long, 37-mm-diameter glass tube, was positioned 6 inches above the plate. The detonator, attached to a small strip of plastic sheet explosive, was secured to the tube, and the water tank was filled.

The explosive charge was detonated directly above the throat section of the segment, thus allowing the detonation to propagate toward each end of the piece. Owing to the pressure distribution produced by this detonation scheme and the geometry of the die, the sheet was first formed into the throat section and then into the larger-diameter portions of the die.

The forming operation forced most of the stainless steel sheet into the die, but did not completely form the ends to the desired contour. Therefore, a second forming shot was required. In this second operation, the die and partially formed sheet were positioned inside the wooden frame, a polyethylene-sheet water bag was placed inside this cavity, and 1/4-pound spherical charges were positioned 8 inches above the center of each of the ends. This second forming shot, which would not have been possible with thinner material (owing to buckling and wrinkling of the plate) completely formed the stainless steel to the desired contour. A stainless steel rib mock-up formed by this technique is shown in Figure 37.

In the course of the subsequent welding experiments, a need arose to fabricate a stainless steel mock-up which contained a V-groove at the throat section of the nozzle. This raised section was to extend into the interface of the explosive-bonding assembly by about 0.050 inch, was to be V-shaped, and was to extend for the full width of the part. This raised section was produced in a completely formed plate by explosively forcing a small center section of the plate into a segment of die which had been grooved to the desired depth. A layer of rubber and several layers of plastic-sheet explosive were placed atop the throat section of the formed plate, which in turn rested on the grooved die. The explosive, upon detonation, forced this section of plate into the V-groove of the die, but did not distort the plate in the adjacent areas. Several plates were formed both with and without the groove, and were used in the mock-up bonding experiments.

Alloy 718 Shells and Rib Mock-Ups

The Alloy 718 components were required for use with the second materials system (Alloy 718 shell and ribs and Hastelloy X liner). As in the stainless steel system, the shell is the main structural support for the other components; the rib mock-ups were to be used to examine the bonding behavior of Alloy 718 in a nozzle configuration. Much the same considerations used in selecting fabrication methods for the stainless steel components were applied in selecting methods for these parts. Were the required raw materials available? Was the proposed method costly? How much development and/or tooling would be required in order to use it?

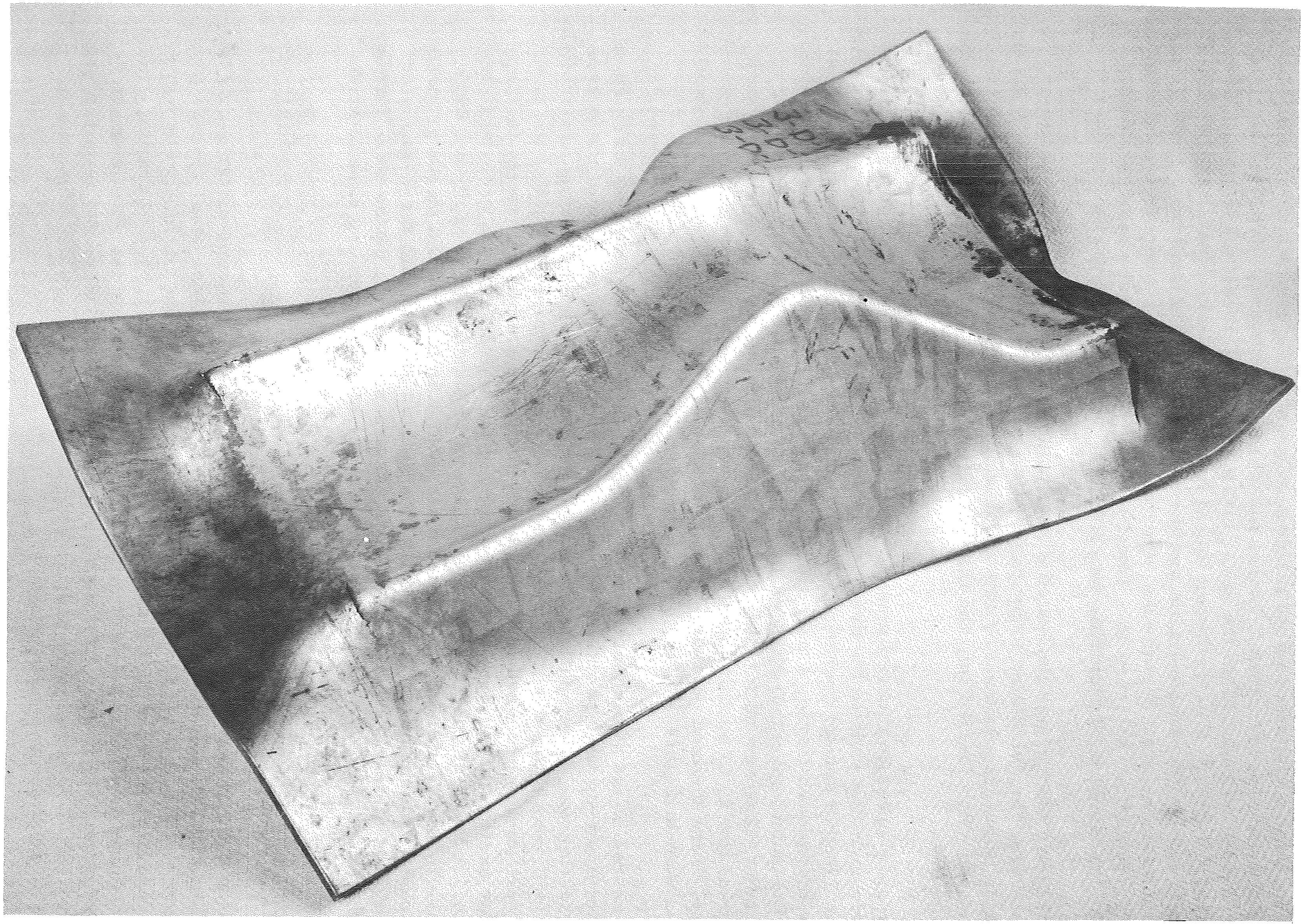

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FIGURE 37. STAINLESS STEEL RIB MOCK-UP EXPLOSIVELY FORMED FROM FLAT PLATE USING SEGMENTED DIE

Edges of formed part have not been trimmed.

The machining of forgings was considered, but was not pursued because no Alloy 718 forgings were available. Forming and machining of a rolled and welded double-conical shape was considered, but was abandoned when it was found that conventional fusion-welding techniques for this alloy would have to be developed. Hydroforming was considered, but was not used, because of the high development and tooling costs.

It was decided that explosive forming of flat sheets into a 72-degree die segment would be the method used. This method was chosen for development because it appeared to be both workable and practical, and because the techniques developed could be used to form the Hastelloy X skins also. (In addition, and as mentioned in the previous section, this was ultimately used, because of its simplicity, to form the stainless steel rib mock-ups from flat plate.)

The method used to form the Alloy 718 shell and mock-ups was similar to that used for forming the stainless steel mock-ups from flat plate. A 72-degree segment of die (the smaller diameter die was used) was positioned on the ground and surmounted with a duplex wooden frame. The plate to be formed was supported above the die on pegs attached to the sides of the frame. A watertight plastic-sheet bag was placed in the cavity. The explosive was positioned, the bag was filled with water, and the plate was formed into the die.

In the first several experiments, attempts were made to form the Alloy 718 sheets directly into the die, but these were unsuccessful. It was not possible to form the sheet completely into the die without fracturing the sheet. If too little energy was used, the workpiece did not completely fill the contour of the die, whereas if too much energy was employed (either by increasing the charge size or by decreasing the charge-to-blank distance) the sheet fractured at the points of maximum strain. Attempts to form the sheet in two or more steps were unsuccessful and resulted in wrinkling and uneven forming in the components.

In order to reduce fracturing, the thickness of the workpiece was artificially increased by sandwiching it between layers of 1/16-inch-thick stainless steel. By this method, it was possible to completely form the Alloy 718 plate into the die without fracturing the workpiece, although, the bottom steel layer was fractured in the process. The charge used in each forming experiment was contained in a 37-mm-ID glass tube and was positioned 6 inches from the workpiece.

The Alloy 718 plates were in the solution-treated condition when formed. Subsequent heat treating to develop the aged properties in the formed plates resulted in distortion of the contour. Several attempets were made to re-form these heat-treated components, but these were not completely successful.

Hastelloy X Liners

The liner component is the thin element which is bonded to the inside diameter of the ribs – the side of the ribs opposite the shell. It is 0.020 inch thick and extends the full length of the nozzle.

Two methods were considered for fabricating the liners – hydroforming, and explosive forming into a female die. Of these two, the explosive-forming method was selected as being most compatible with the overall program objectives. The required nozzle segments were fabricated by explosively forming flat sheets into a 72-degree segment of die, using the approach and procedures outlined above. Considerable effort was expended in attempting to form these components. However, because of their thinness, difficulty was experienced in fully forming the parts without causing them to tear or fracture at the points of maximum stretch. The sheet had to be formed in a single operation, since all attempts at multiple forming led to severe wrinkling and distortion.

The tendency to tear was reduced to some extent by laminating the Hastelloy X sheet between layers of mild or stainless steel and then forming this composite into the die. This modification resulted in an increase in formability of the plates, as the plates would fill the die more completely before fracturing occurred. Complete forming, however, could not be achieved.

This technique was extended further and resulted in a method suitable for completely forming the Hastelloy segments. A flat sheet of Hastelloy X was placed between two layers of 1/4-inch-thick aluminum, and this composite was formed into the die using a 37-mm-diameter charge placed 6 inches from the plates. The components formed completely into the die without fracturing. The formed liner component was dimensionally inspected and found to be suitable for use.

Ribs

For each of the two materials systems, two types of ribs were required - continuous full-length ribs, and discontinuous ribs which terminated near the throat section of the nozzle. These details are shown in Figure 29. Each 60-degree nozzle segment required 21 ribs, 11 of them being full length, which the remaining 10 were discontinuous. Each of the ribs was 0.105 inch high and 0.040 inch wide, and each was curved to conform to the nozzle contour.

Two methods were considered for fabricating these curved ribs. One method would require machining them from 0.040-inch sheet stock using a contour mill, and the other would involve press forming the ribs from preground, straight strips. Each of these methods had some desirable features, while each had drawbacks. Press forming the ribs with a single-acting matched die would be a simple, straightforward operation, but would be a difficult operation to control. Provisions would have to be made to control factors such as dimensional uniformity, springback corrections, etc. On the other hand, machining the ribs from sheet stock should provide a uniformly high-quality product, but would be an expensive operation.

Quotations for machining the ribs were solicited from several fabricators. The costs were so greatly above the amount anticipated that this approach was abandoned, and it was decided to fabricate the ribs by press forming from flat stock.

The raw materials required for the press-forming operation were prepared by shearing flat sheets of 0.040-inch-thick 304 stainless steel and Alloy 718 into strips 1/4 inch high by 21 inches long. These strips were straightened, welded into packs of approximately 35 ribs each, annealed, and ground to a height of 0.105 inches.

With both Alloy 718 and stainless steel strips were sheared and ground to size, only the stainless steel strips were fabricated into ribs. The Alloy 718 strips were held in reserve pending the results of experiments with the stainless steel system, and ultimately were not used. The stainless steel ribs were fabricated to shape by bending in a single-acting mating die set.

The die set used to form the ribs was fabricated from 1/2-inch-thick mild-steel plates. It consisted of matching, curved halves which were held in vertical alignment during pressing by a long vertical pin at each end. The die contour was similar to that of the nozzle, but differed from it in two respects. It was modified to provide for the springback of the ribs during forming, and also was later modified (as a result of the concurrent experimental explosive-welding work – detailed in a later section) to provide more suitable collision conditions over the full length of the nozzle during rib-to-shell welding.

Mild-Steel Support Tooling

The mild-steel support tooling serves to position, support, and separate the rib components during the rib-to-shell welding operation. In addition, during the liner-to-rib welding operation, it supports the ribs, keeps them in the proper orientation, and fills the channels to prevent them from collapsing.

The complete rib-and-rooling assembly needed in the welding operation could be assembled in one of two ways. In one of these methods, which had been used in Task I, the ribs and tooling are separate elements. These elements are laid side-by-side to form a "solid" plate, which is then explosively welded to the base component. In the second method, used in Task II, a solid plate of the tooling material is slotted, the ribs are inserted, and this assembly is then used in the welding operation. Figure 38 illustrates these two options for a flat-plate configuration. Experience with both of these systems has shown that they perform equally well, provided they are properly made and assembled. Since they perform in the same way, the choice of which to use depends on other factors, the most important of which is the ease of fabrication and assembly.

FIGURE 38. TWO METHODS OF FABRICATING RIB-AND-TOOLING ASSEMBLIES

While either of the above methods could be readily extended for use with a cylindrical configuration, this is not true for a nozzle shape. In fact, both methods appeared equally difficult to use for nozzle fabrication. Of the two methods; however, the solid slotted nozzle appeared to offer some slight advantages. Therefore, it was planned to use this method.

To use this method, a mild-steel nozzle was required. Three methods were considered for its fabrication. One of these was the explosive expansion of commercial thick-walled pipe, and a second was machining from a hollow steel billet. The third method consisted of rolling and welding two flat sheets to provide a double-truncated conical configuration. This rough nozzle shape could then be either machined (if the starting material were thick enough) or explosively sized into a die (for thinner starting material). Whichever method was used, the completely formed solid mild-steel nozzle would then be slotted on a contour mill and sectioned into 72-degree segments for use in the bonding experiments. The extremely high estimated cost of slotting the tooling fixture led to abandonment of the solid-tooling concept.

The alternative tooling concept - use of individual tooling elements - was therefore pursued. These tooling elements had a most unusual and hard-to-fabricate shape, as shown in Figure 39. Each element was 0.100 inch high and was bent to the curvature of the nozzle. Not only were the pieces curved, but the width of each element changed as a direct function of the axial location (or more precisely, the radius at a given axial location).

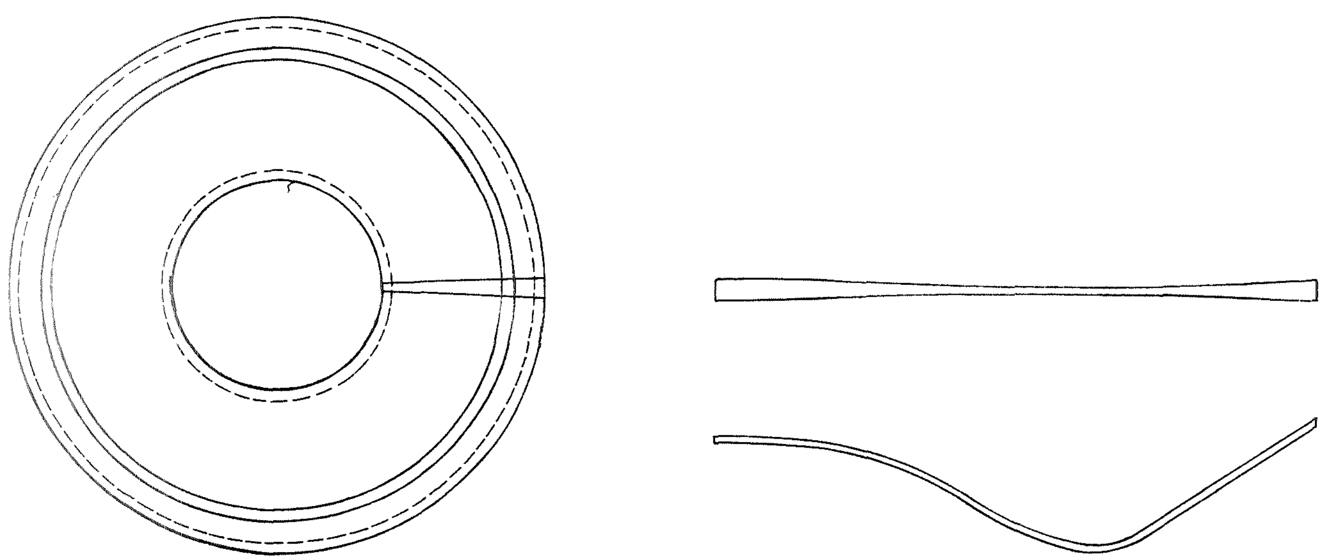


FIGURE 39. MILD-STEEL TOOLING ELEMENT FOR NOZZLE-SECTION WELDING SETUP

The tooling elements were fabricated from mild steel. Flat strips, 21 inches long by 3/8 inch wide by 1/8 inch high; were ground to a height of 0.100 inch, the height of the channel. They were then press formed to the proper curvature in the same die used to form the ribs. To achieve the variable width, which on analysis of Figure 39 can be seen to be equivalent to (or the result of) a 2-1/2-degree taper, the formed piece was positioned on a special fixture and ground. This fixture, shown in Figure 40, consisted of a ground-steel block which had a top surface angled at 2-1/2 degrees to the horizontal and a number of locating pegs (to hold the tooling piece securely in place during the grinding operation). Each tooling piece was ground until the proper thickness at the thickest point (the point of maximum diameter in the lay-up) was reached. These tooling elements were then combined with the ribs and used in the rib-welding experiments.

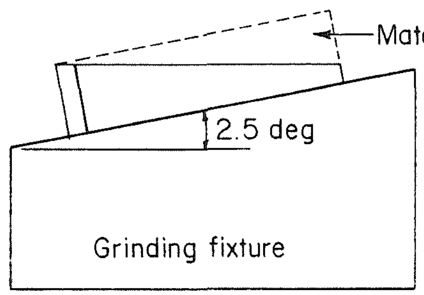


FIGURE 40. FIXTURE USED TO FABRICATE MILD-STEEL TOOLING ELEMENTS

For clarity, positioning pegs are not shown.

Explosive Welding of Curved-Section and Nozzle Components

The feasibility of explosive welding of channeled nozzle segments was examined in a stepwise, systematic manner. Concurrent with the component fabrication effort described in the previous section, a number of preliminary experiments were run to examine the various individual aspects of the entire nozzle-welding problem. Explosive-welding experiments were then run using the previously fabricated nozzle-shaped components, and were followed with several experiments in which rib-to-shell nozzle welding was attempted.

Welding of Ribs and Tooling in Flat-Plate Configuration

Discontinuous Rib Welding. Among the many problems unique to the explosive welding of nozzle segments was the presence of discontinuous ribs in the nozzle. These ribs, which can be seen in Figure 30 (showing a drawing of the nozzle segment), do not extend the full length of the nozzle but "stop" at the throat section. As this drawing shows, every other rib is discontinuous.

This discontinuous-rib configuration would be produced in the nozzle through use of a modified rib-tooling assembly in the rib-to-shell welding operation. Where full-length ribs were required, full-length stainless steel elements would be inserted into the tooling structure. Where discontinuous ribs were needed, however, a three-section "rib" would be used. The center section (the section which extends over the throat) would be mild steel, whereas stainless steel ribs would be used at each end of the nozzle. After the liner-to-rib welding operation, the mild-steel rib would be removed during acid leaching of the tooling, thereby producing the required discontinuous rib.

While these multipart ribs could be easily incorporated into the rib-tooling composite, another problem was foreseen. Past experience with similar explosive-welding configurations indicated that bonding might be difficult at the points of transition, i.e., from mild steel to stainless steel or vice versa. In past work, these areas of transition have resulted in areas of nonweld. This was also verified in the initial end-cover welding studies in Task II.

Two flat-plate explosive welding experiments were performed in order to define and solve this problem. In these experiments, stainless steel and mild-steel ribs were held in slotted mild-steel tooling plates and welded to stainless steel base plates. The base-plate assembly for such an experiment is shown in Figure 41. Each full-length slot contained several sections of rib, with mild-steel and stainless steel ribs alternating along the length of one slot. By this means, it was possible to examine the effects on the welding behavior of both types of transition – from stainless steel to mild steel (a "stopping" transition as at A), and from mild steel to stainless steel (a "starting" transition at B). The tooling plate in each experiment contained several slots; it was therefore possible to examine many potential solutions in a single experiment.

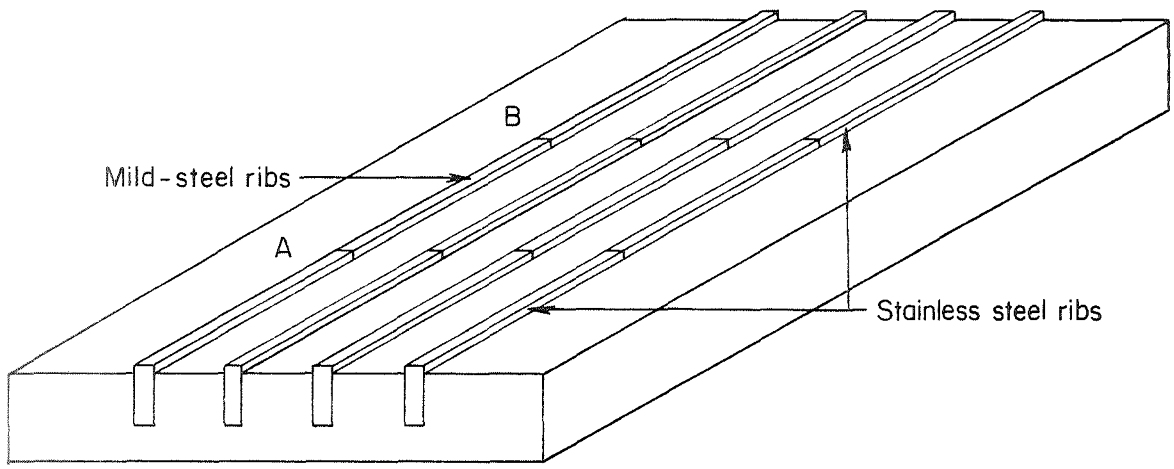


FIGURE 41. RIB-TOOLING ASSEMBLY USED IN STOP-START RIB-WELDING EXPERIMENTS

The first experiment showed that a "stopping" transition could be accomplished with no loss of welding over the full length of the stainless rib. Continuous welding was achieved, even at the end of the rib adjacent to the mild steel. However, this same experiment showed that a "starting" transition resulted in nonwelding for a distance of about 1/4 inch from the end of the stainless steel.

In a second experiment, various solutions to this problem of starting-end nonweld were investigated. In this experiment, the heights of the mild-steel tooling elements were changed from slot to slot so as to provide variously sized "steps". In addition, bent and chamfered ends on either the mild-steel or stainless steel elements were incorporated to provide other geometries of transition. It was found that welding to within 0.015 inch of the starting end of a stainless steel rib could be achieved through adjustments of the clearances at the rib ends. End welding was accomplished in a system in which the end of the mild-steel tooling "rib" which was upstream of the stainless rib was about 0.010 inch below that of the stainless rib.

Welding of Curved Plates

In the introduction to this report, the technological and historical framework within which this program was conceived was outlined. This section discussed the fact that explosive welding has not been successful in welding surfaces curved in the direction of detonation, although the process has been extensively used to weld both flat plates and cylinders. It was noted that in both of these applications, the welding direction was a straight line, and thus the jet produced by the colliding plates could egress from between the components. It was further noted that curved segments were not thought to be weldable.

This limitation was believed to be an artificial one imposed (perhaps unconsciously) by the present form of the theoretical analysis of the explosive-welding process. Specifically, the physical model used to illustrate the phenomenon of jetting shows the high-energy jet created by plate-to-plate impact being expelled from the interface at an angle which roughly bisects the angle of collision. The jet, according to this picture, would be expelled from the system in straight-line welding. However, it would not be expelled when the plates were curved, but would impact one of the plates, cause surface melting of that plate, and consequently form a weak weld. This schematic picture has been used to explain the poor results normally attendant to curved-plate welding. The lack of practical success and a theoretical treatment to justify these poor results have led to the generalization usually accepted by explosive welders, namely, "curved sections cannot be successfully welded".

In this program, the problem was approached from the opposite direction, and the self-imposed limitation was examined for its validity. It was believed that the injunction against curved-plate welding was not "real", and further that, through careful, close examination of the details of the process, it might be possible to overcome the supposed limitation on welding of curved plates.

The first task was to define the problem of welding of a curved surface more precisely. What happens when curved-plate welding is attempted? What are the results when no special precaution or process modifications are incorporated? To answer these questions, the experimental arrangement shown in Figure 42 was used. Two 1/16-inch-thick metal plates, each bent to a radius of 1-1/2 inch in the radius of curvature of the nozzle's throat section, were positioned with a nominal 1/16-inch gap between them. The base plate rested on a steel support anvil, which in the first experiments was composed of several separate elements fitted together to form an anvil of the required curvatures. A 9/16-inch-thick layer of Trojan SWP-1 explosive was used to weld the plates. In these experiments, the explosive charge was detonated at one end of the plates.

Three welding experiments were performed, using this configuration, in the first series. As Table 8 shows, mild-steel and stainless steel plates were used. The welds between the plates were evaluated by either metallographic examination and/or study of the surface of the stainless steel plate after acid removal of the mild-steel plate. The

TABLE 8. CURVED-PLATE WELDING EXPERIMENTS

Plates were 1/16 inch thick except as noted.

Experiment	Materials			Detonation Mode	Other
	Cladder Plate	Base Plate	Support Anvil		
C-1	Mild steel	Stainless steel	Composite (mild steel and Wood's metal)	End	
SA-1	Stainless steel	Mild steel	Three-piece mild steel	End	Interface was evacuated.
SA-2	Ditto	Stainless steel	Three-piece mild steel	End	
SAC-1	Mild steel	Ditto	Solid mild steel	End	
SAC-2	Ditto	"	Ditto	End	Interface was evacuated.
SAC-3	"	"	"	Center	
SAC-4	"	"	"	Center	
SAC-5	"	"	"	End	Base plate was 3/16 inch thick
SAC-6	"	"	"	Center	Depression at apex of curve. Deta-sheet strip above this depression.
SAC-7	"	"	"	Center	Depression at apex but smaller than in SAC-6; base plate was initially welded to anvil.

results of one of these experiments is shown in Figure 43. This figure shows the top surface of a stainless steel plate to which a mild-steel plate had been welded. The mild-steel plate was removed by dissolving it in nitric acid, thereby revealing detail of the welding interface such as the fine detail of wave structure and the extent of interfacial melting and nonwelding.

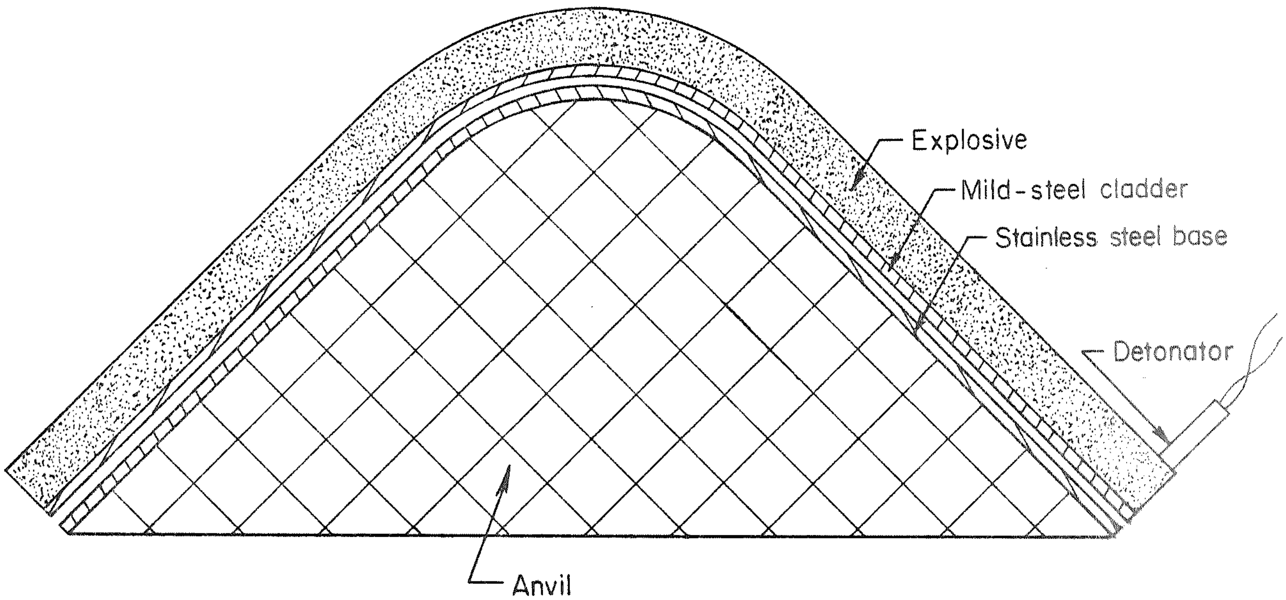


FIGURE 42. CURVED-PLATE WELDING ASSEMBLY

Figure 43 illustrates the problems associated with welding of curved plates with no special precautions. It also provides considerable insight into the behavior of a "normal" (i.e., unmodified) curved-plate explosive-welding system. The figure is oriented with the point of detonation at the left. The detonator, or blasting cap, was positioned in the center of the plate at A. No ripples or waves can be seen at this point. A short distance to the right (at B) the surface is disturbed, and welding has begun. The size of the waves increases until, at C, the system has stabilized and the wave size becomes uniform. It remains constant until, at D, the curvature of the plate is encountered. Because of this curvature, the collision angle has changed and led to the occurrence of larger waves, immediately followed by areas of no welding (at E). The wave pattern then resumes, and continues until the top of the curve is reached (F). The weld degrades rapidly, and areas of melt trapment (G), heavily worked but nonbonded areas (H and J), and areas of extensive melting (I and K) can be seen. Immediately to the right of Point K, which is located at the back end of the curve, the normal wave pattern is re-established and continues, with small localized differences, to the end of the sample.

The other samples in this initial series showed small qualitative differences from the above, although the same basic features were present. Because it was thought that air entrapment might be contributing to the excessive melting, one of these samples was bonded using vacuum between the plates. No difference in behavior was noted, however.

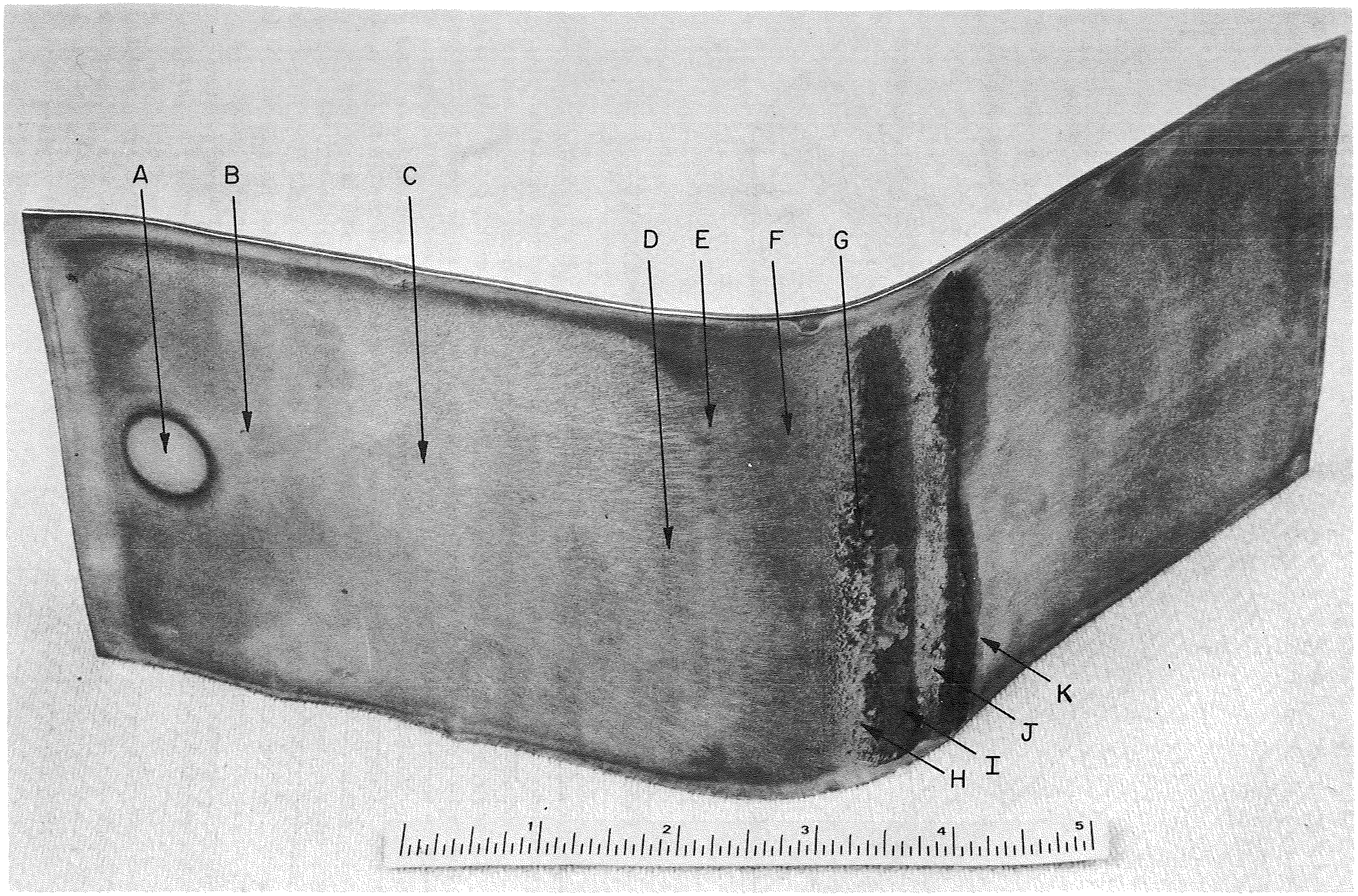


FIGURE 43. STAINLESS STEEL BASE PLATE SHOWING RESULTS OF CURVED-PLATE WELDING EXPERIMENTS

Mild-steel cladder was removed by acid leaching.

The first series of experiments showed that poor-quality welds are produced between curved plates, and that the extent of poor welding is quite sensitive to small differences in spacing between the plates. It was also noted that good contact between the base plate and the anvil had to be maintained, as the base plate would otherwise "lift off" and "gather" ahead of the collision point during welding.

This series of experiments revealed the major problems associated with the welding of curved plates, and generated qualitative data against which other experimental results could be compared. These experiments also demonstrated that extreme care would be needed in assembling any future experiments.

On the basis of these results, a second series of experiments was conducted, using the same setup as in the initial series. These experiments, which are listed as the "SAC" series in Table 8, differed from the initial experiments in several respects. In each of the experiments, the plates were carefully bent to the required curvature and then hand fitted to achieve more accurately spaced gaps between the plates. The support anvils were solid blocks of mild steel, as opposed to the multiple-piece anvils used in the first series. Also, some of the experiments employed a different explosive detonation scheme, and were detonated at the top of the curve rather than at one end. As Table 8 shows, several of the experiments in this second series were repeats of experiments which had been performed in the initial set of experiments; this was done to establish confidence in the results noted, and to insure that the results were not being masked by extraneous factors (such as poor base plate-to-anvil contact or inaccurately spaced plates).

The results of the end-detonated experiments were similar to those of the first series. The reproducibility was improved considerably, although the weld quality was not. In fact, the first two experiments exhibited larger areas of melt than did the equivalent earlier experiments. In one of these experiments, an evacuated interface was employed; no improvement in weld quality over that attained with an unevacuated interface was noted. In another of the experiments, a thicker base plate was used; again, no improvement was seen.

The first of the center-detonation experiments resulted in a marked improvement in the weld quality and a considerable decrease in the extent of melting. However, the areas under the detonator and immediately adjacent to it were not welded. This nonweld area was considerably reduced in subsequent experiments through use of a modified cladder plate, which was formed with a slight narrow depression at the apex of the curve. This ridge extended the full width of the plates, was about 0.040 inch deep, and projected into the interface gap between the plates. Plates welded using this technique were almost completely welded, and those areas which were not welded did not show any areas of melting.

Welding of Stainless Steel Mock-Ups to Shells

In the curved-plate experiments discussed above, the welding behavior of curved interfaces was examined, and it was found that the major problem was nonwelding and melting in a section "downstream" of the most severe curvatures. This work also indicated that these defects could be minimized by detonating the explosive in the area of maximum curvature and allowing the detonation to propagate in both directions from this point.

These results were applied to welding of nozzle segments. Two experiments were run in which 3/16-inch-thick stainless steel nozzle-shaped elements (rib mock-ups) were welded to full-thickness stainless steel shell components. In one of the experiments, the explosive employed was detonated at one end of the assembly, while in the other, the explosive was detonated in the center.

The experiments were assembled from components whose fabrication was described above. One other element was required for these welding experiments – a container or holder for the explosive charge. This charge holder, whose positioning and use are shown in Figure 44, was made from a cylinder of expanded polystyrene foam. A complate 360-degree nozzle-shaped element was machined from the cylinder of foam on a tracer lathe and sectioned into five 72-degree segments for use in the nozzle welding experiments.

The component arrangement used in the welding experiments is shown in Figure 44. In addition to the components already discussed, this figure shows two side plates which served as vital parts of the assembly. These wooden plates were used as supports for the entire charge-container/explosive/cladder-plate assembly, and were also used to physically confine the edges of the explosive charge during loading and handling.

The following steps, common to both experiments in this series, were used in assembling the welding runs. The shell was placed onto the support anvil, with a thin layer of silicone grease placed between the shell and the anvil to insure good shock-wave transmission across this interface. Small tabs of metal of the required height were used to achieve the desired spacing between the shell and the mock-up. These spacers were attached to the shell by glueing one to each of the shell's four corners.

Special fixtures and procedures were used in loading the explosive charge. The two wooden side plates were placed into a V-shaped frame, and the foam charge holder was inverted and placed between them. The edges between the plates and the charge holder were sealed with modeling clay to prevent leakage of the powered explosive, and small sections of clay were placed at each end of the assembly to confine the ends of the explosive charge. A uniform 9/16-inch-thick layer was packed onto the curved surface of the charge holder. The cladder plate was then positioned atop this explosive load and secured to the charge holder with tape. The explosive-cladder plate assembly was inverted and carefully positioned above the shell on the spacers. A detonator was attached prior to detonating the explosive charge.

The first experiment used an end-detonated 9/16-inch-thick explosive charge and employed a gap between the plates of 0. 120 inch. The charge-initiating assembly consisted of a line-wave detonator and an additional strip of plastic-sheet explosive to insure complete detonation of the main explosive charge. This detonation package was attached to the charge holder at the divergent end of the nozzle (Station 1).

The first experiment produced welding over most of the interfacial area. However, several areas of nonweld were noted, as shown in Figure 45. Ultrasonic examination revealed two areas of the nozzle that were not welded – one in the divergent end of the nozzle near the change in the nozzle's curvature, and the other in the convergent end just beyond the throat. Metallographic examination of a section taken from the centerline of the segment further defined the locations and nature of the nonwelded sections. One of these areas extended between Stations 2 and 3 (at the start of the curve), and the other was located between Stations 8 and 10 (starting at the throat and extending 2 inches beyond it). The remainder of the nozzle segment was well welded.

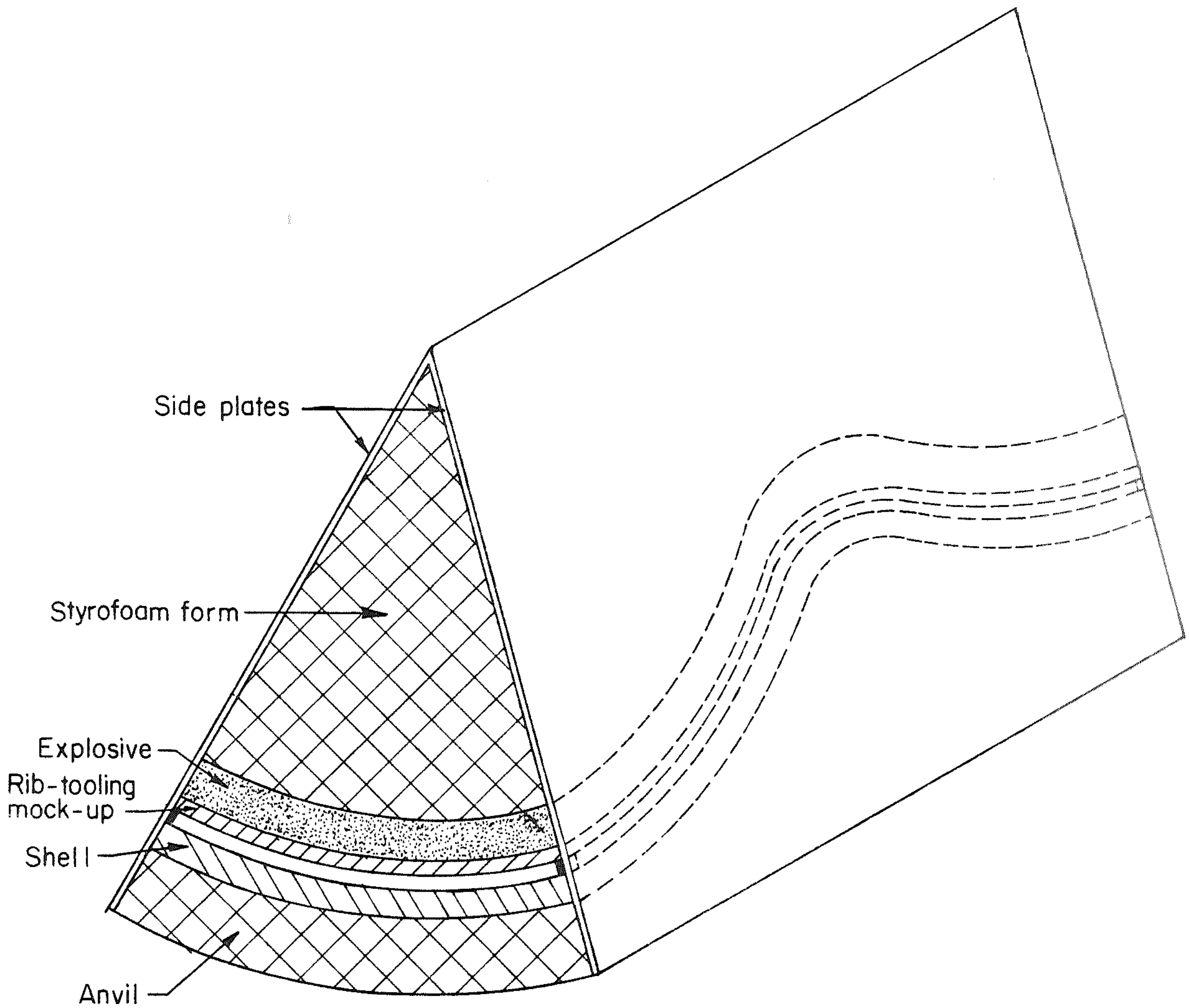


FIGURE 44. ARRANGEMENT USED FOR EXPLOSIVELY WELDING STAINLESS STEEL NOZZLE SEGMENT COMPONENTS - RIB TOOLING MOCK-UP TO SHELL

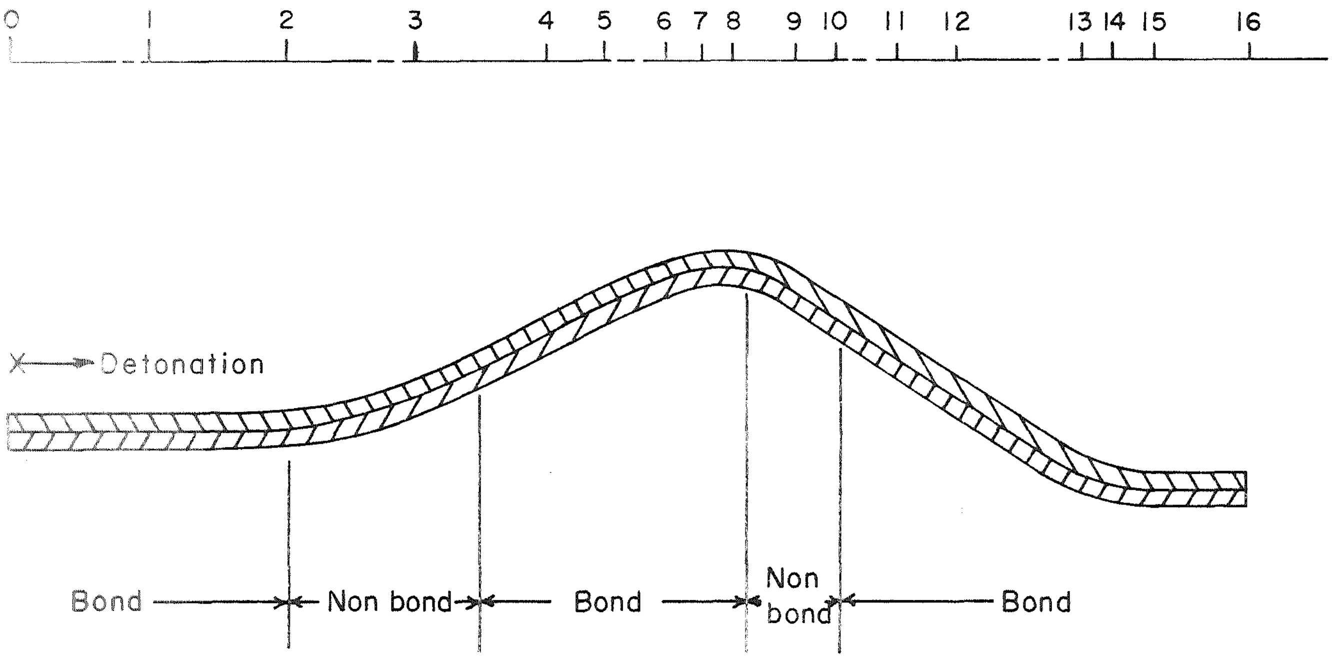


FIGURE 45. SCHEMATIC SHOWING BONDED AND NONBOND AREAS IN FIRST STAINLESS STEEL MOCK-UP-TO-SHELL WELDING EXPERIMENT

The nonwelded section at the beginning of the curve (between Stations 2 and 3) exhibited a melt zone at the interface, and a crack, which was about 0.005 inch wide at the widest point, ran through the center of this melt zone. The other nonwelded area was more deeply melted, and the crack was much wider, measuring 0.020 inch at its widest point.

The second-welding experiment was setup in a manner similar to the first, but differed from it in several respects. The gap between the plates was increased to 0.150 inch, and a center detonation scheme was used. This central detonation was achieved by attaching a small strip of plastic explosive to the charge holder at the throat section (Station 8) prior to loading the main charge. Also, the charge holder contained a small hole at this point through which the detonator was attached. The rib mock-up in this experiment contained, at Station 8, a small V-shaped protrusion which extended into the gap between the plates.

The results of this experiment were considerably different from those of the first. While the two plates were welded, the type and location of the defects were different. The nonwelded areas at the interface appeared as narrow cracks and contained no molten layers.

Four areas of nonbond were noted as shown in Figure 46. As expected, one of these was located just under the detonator, and extended longitudinally for 3/8 inch on each side of it. The secondarea was found between Stations 10 and 11, and appeared as a thin crack between the plates. It appeared to be the result of welding conditions (plate collision angle, velocity) which were slightly lower than those required to achieve a satisfactory weld. The other two nonwelded areas were located at the ends of the sample, and both had the appearance of good welds which had been broken (most likely by cracks which originated at the ends of the sample and propagated into the interface). The crack at one end was 5-1/2 inches long; the other end was cracked for a distance of 3-1/2 inches.

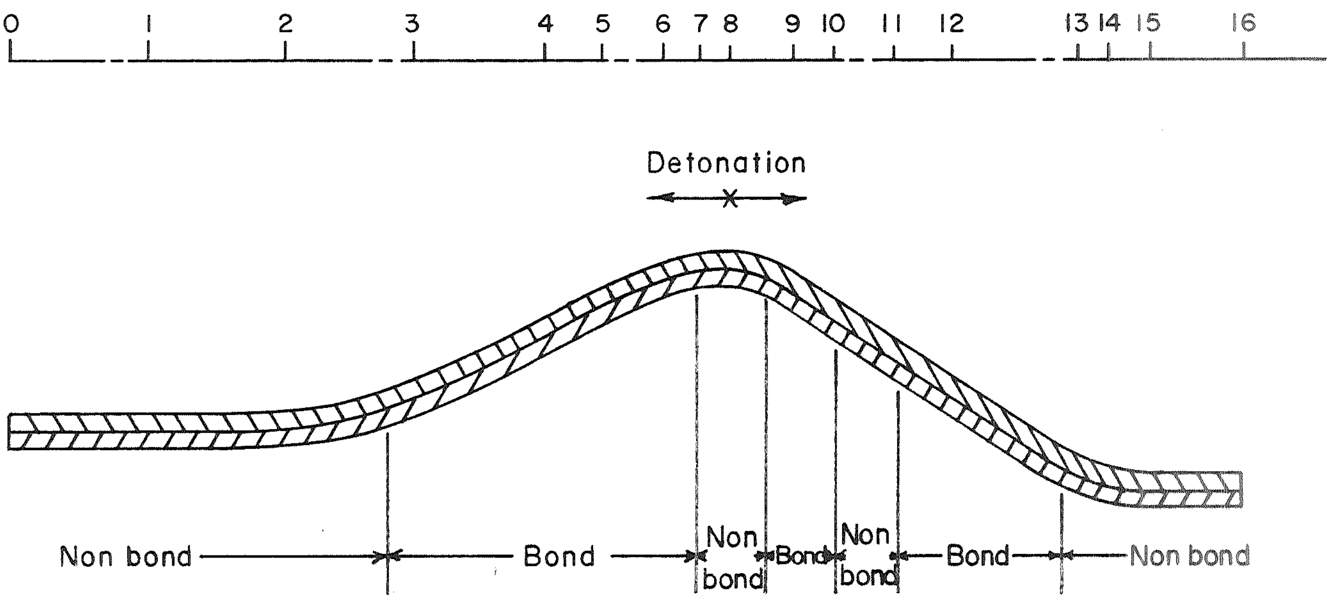


FIGURE 46. SCHEMATIC SHOWING BONDED AND NONBOND AREAS IN SECOND STAINLESS STEEL MOCK-UP-TO-SHELL WELDING EXPERIMENT

In terms of overall quality of the welding achieved, these two experiments yielded equivalent results. Both were welded over most of the interface, but neither had achieved the degree of weld quality required in a reliable, high-quality, well-welded nozzle.

Welding of Angled Plates and Truncated Pyramids

Because of results obtained in the rib mock-up welding experiments, the curved-plate approach used earlier in this task to examine non-straight-line welding was revived. The approach was modified, however, in that angled plates were used in the welding experiments in place of the curved plate used in the first series. This change was made for several reasons, the most important being:

(1) The sharp transition in detonation and welding direction at the point of inflection would be a more severe test of any proposed solution, and any change which was proved to be effective in the angled-plate situation should also be workable for the curved-plate case.

(2) The geometric relation (collision angles, etc.) between angled plates at various stages of the welding operation could be easily analyzed, whereas the curved-plate case required a more complex analytic approach.

(3) The experimental variables (gap between plates, contact with the support anvil) could be controlled more closely.

The experimental assembly used in these experiments is shown in Figure 47. Briefly, it consisted of a 1/8-inch-thick cladder plate bent into an inclined step, providing an obtuse angle (less than 180 degrees – as at A) and a reflex angle (greater than 180 degrees by the same amount – as at B). The base plate (where used) and the anvil were fabricated to the same contour.

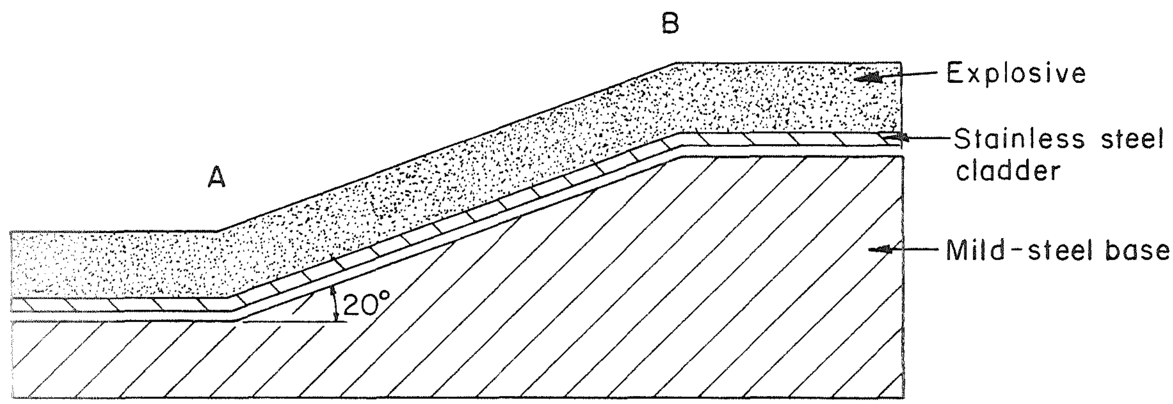


FIGURE 47. EXPERIMENTAL SETUP FOR STUDYING EXPLOSIVE-WELDING CHANGE OF DIRECTION

Five experiments were run to determine the quality of welding which could be produced at the points of inflection. The first of these experiments was designed to provide a baseline or point of comparison to which the results of the other experiments could be compared. In this experiment, the plates were positioned with their apices one above the other, and the plates were separated to provide gaps of 0.100 inch between the horizontal steps. The other experiments in this series incorporated various modifications of this basic assembly. The changes made were based on various theoretical and practical considerations and were believed to offer chances of improving the welding behavior. In one of these experiments, powdered explosives having different detonation velocities were positioned at the points of inflection, while the normally used SWP-1 was employed at the other sections. Other experiments were assembled with the cladder plates moved longitudinally with respect to the bare component by various amounts. The reason for this offset is discussed below.

The first experiment yielded plates which were welded over most of the interfacial area, but were not welded at either of the points of inflection. Metallographic examination of sections taken at these points revealed areas of nonwelding, melting, and jet entrapment downstream from both of the angles. Geometric analysis of the welding conditions existing at these two points (see the Appendix for this analysis) indicated strongly that the poor welding behavior at these points and slightly beyond resulted from a longitudinal movement of the cladder plate during the welding operation. This analysis also suggested that an offsetting longitudinal movement in the direction opposite to the detonation direction during assembly of the components would decrease the amount of poor welding.

This longitudinal offset was tested in the last several experiments in this series and was found to provide a satisfactory solution to the problem. An offset of 0.080 inch in the direction opposite to that of detonation yielded a complete, defect-free weld over the entire length of the plates. No areas of nonweld or melting at the interface could be detected.

In the next series of experiments, attempts were made to test this solution using a curvature more similar to that of the nozzle. The most obvious choice for simple experiments would be curved plates, but as discussed previously, plates of this geometry are difficult to fabricate accurately. Therefore, to maintain the advantages of precision and geometric analysis, truncated pyramidal shapes were used. In each of these experiments, a 0.060-inch-thick stainless steel plate was clad to the three exposed surfaces of a trapezoidal mild-steel base. Uniform-thickness charges of 9/16 inches of SWP-1 explosive were used as the welding charges.

Two experiments were performed. The arrangements employed are shown in Figure 48. In the first of these, a uniform standoff gap of 0.060 inches was maintained between the plates on each of the three faces. This spacing required that the apices of the cladder-plate angles be positioned relative to those of the base as shown in Figure 48. In the second experiment, both of these angles were shifted in the direction

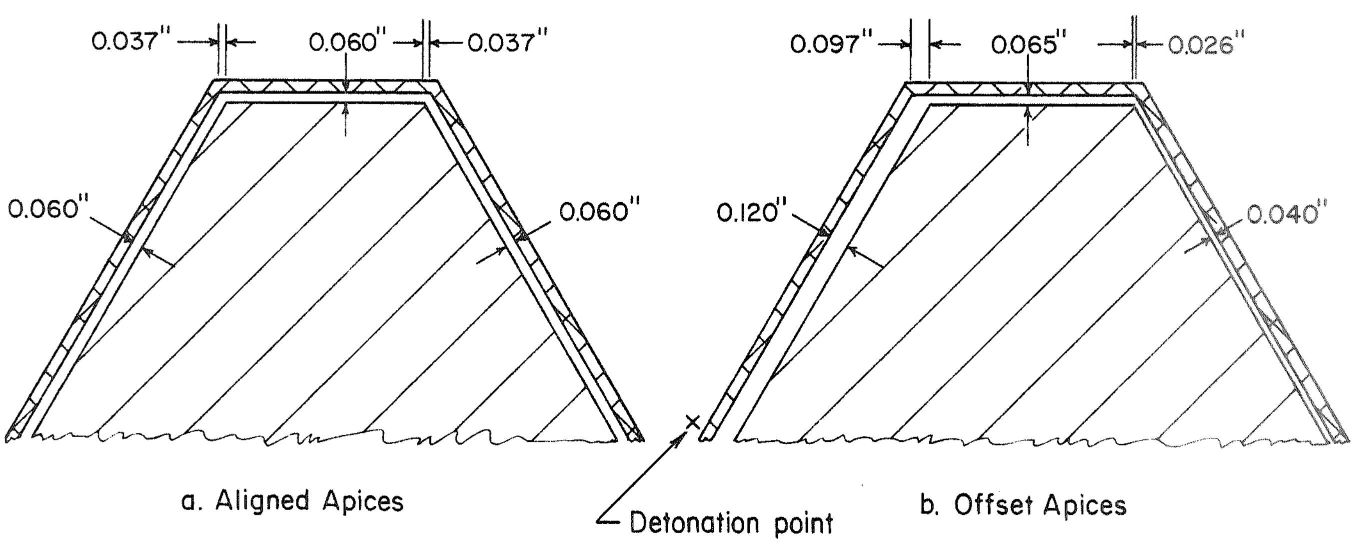


FIGURE 48. ARRANGEMENTS EMPLOYED IN TRUNCATED-CONE EXPERIMENTS TO EXAMINE EFFECT OF OFFSETTING THE APICES

opposite that of detonation. Because of the geometrics of this configuration, it was impossible to use this arrangement without also changing the standoff between the plates. Thus the spacings shown in Figure 48b were used.

The results of these two experiments are shown in Figure 49. As can be seen, the offset-of-angle method resulted in considerably improved welding at points downstream of the direction change. The amount and extent of nonwelding was considerably reduced, and the regular, interlocking wave pattern characteristic of "good" explosive welds was resumed in shorter distances at both of the corners in the second experiment.

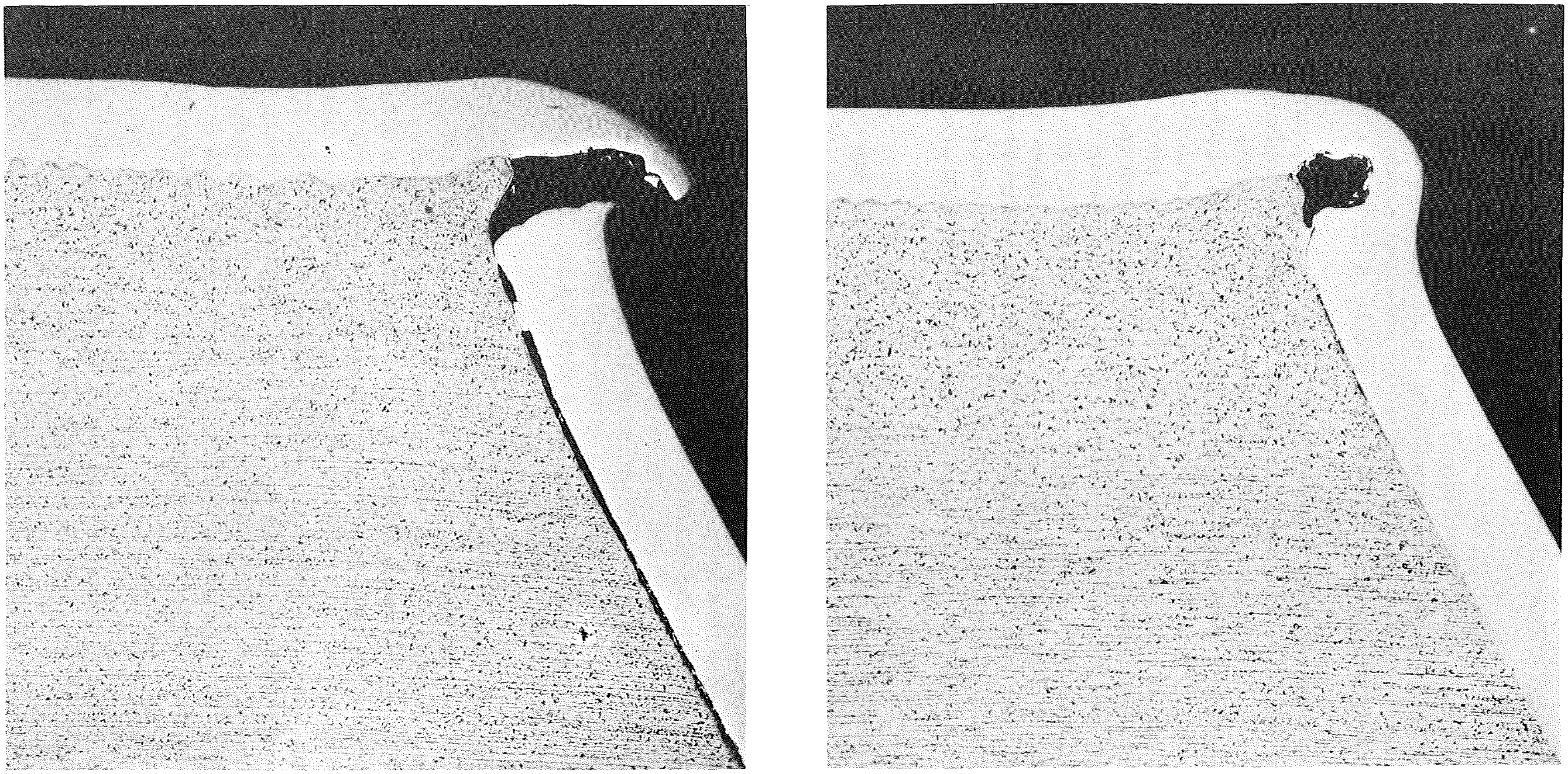
While these experiments showed that this offset method was effective for improving the weld quality between angled plates, the question remained – would a similar solution be applicable to curved-plate welding? A cursory geometric analysis indicated that it would, since the major problem (loss of collision angle with change in direction) was the same in both cases. Therefore, in the case of curved-component welding, an offset would reduce the extent of low-angle collision and would increase the extent of welding. This offset could be accomplished by modifying the curvature of the cladder plate, particularly in the area of maximum change of welding direction (i. e., at the throat section of the nozzle).

The change of curvature required for the nozzle configuration was estimated on the basis of the results of the above experiments, a cursory geometric analysis, and a knowledge of plate-acceleration kinetics. The coordinates of this new curvature are given in Table 9. These coordinates were used to fabricate the bending die which was used to press the ribs and tooling to the proper curvature. Thus the components used in the rib-to-shell welding experiments incorporated the offset-angle curvature.

TABLE 9. CHANGE IN COORDINATES OF RIB CURVATURE

Modification was made to promote welding in the throat section.

Station	Longitudinal Dimension (X), inches	Original Radial Distance (Y), inches	Modified Radial Distance (Y), inches	Rib-to-Shell Spacing, inch
0	0.00	5.14	5.14	0.120
1	2.00	5.14	5.14	0.120
2	3.99	5.11	5.11	0.120
3	5.93	4.65	4.69	0.120
4	7.75	3.75	3.77	0.100
5	8.62	3.26	3.30	0.080
6	9.49	2.93	2.98	0.070
7	10.08	2.78	2.84	0.060
8	10.43	2.75	2.82	0.050
9	11.38	3.04	3.10	0.060
10	11.99	3.43	3.49	0.070
11	12.86	4.00	4.04	0.080
12	13.73	4.57	4.60	0.090
13	15.55	5.71	5.71	0.120
14	16.05	5.86	5.86	0.120
15	16.63	5.96	5.96	0.120
16	18.00	5.96	5.96	0.120



10X 7E036

a.

10X 7E038

b.

FIGURE 49. EFFECTIVENESS OF OFFSETTING THE CLADDER PLATE WITH RESPECT TO THE BASE

The figure on the left was not offset, whereas the cladder plate in right-hand photograph was moved to the left 0.040 inch.

Welding of Ribs and Tooling to Shells – Nozzle Configuration

Two full-section stainless steel rib-to-shell welding operations were performed. In these experiments, ribs and tooling were employed which had been fabricated in accordance with the modified curvature developed in the previous section. Only full-length ribs (no discontinuous ribs) were welded to the shells in this work.

In each of these experiments, the rib/tooling composite plate was assembled from individual ribs and tooling pieces. The required number of ribs and tooling bars (20 and 21, respectively) were carefully positioned to form one-sixth of a nozzle. A set of mild-steel fixtures curved concavely to the radius of the nozzle at several points were used as supports for this fixturing. Several strong magnets were attached to the positioning fixture which then held the mild steel firmly in place. The stainless steel ribs were interspersed between the tooling bars and held in place by contact with the tooling. The elements in this composite plate were then secured and locked in placed by soldering them together using four bands of solder – two at each end. At each end, a band was located at the extreme end of the segment and the other was placed about 4-1/2 inches from the end. A layer of latex paint was applied to the concavely curved top surface of the rib-tooling composite as a sealant for the longitudinal gaps between the individual elements, and this prevented the powdered explosive from leaking through into the interface gap during handling.

The two components to be welded in the first experiment – the rib-tooling composite plate and the shell – are shown in Figure 50. The shell was placed in a die segment, to which a thin layer of silicone grease had been applied. A foamed-polystyrene charge holder was positioned between two wooden side plates, and the explosive charge was loaded onto the top surface of the charge holder. The composite cladder plate was placed on the explosive charge and secured with tape, after which the charge assembly was inverted and placed on spacers which had been cemented to each corner of the shell. The detonator was attached and the charge fired. In both of these experiments, the same welding parameters were used – a 9/16-inch-thick layer of SWP-1 explosive and a nominal interfacial gap of 0.120-inch at the ends of the nozzle. Both of the experiments were end-detonated at the divergent end of the nozzle (Station 1). Each of them employed a line-wave generator to detonate the charge.

Examination of the components revealed that the first welding experiment yielded very poor results. The ribs were welded to the shell only at the detonation end of the assembly. The welds extended for a length of 4 inches and then stopped. Close examination of the remainder of the components showed that the inside surface of the shell had not been deformed, as the machining marks were undisturbed and clearly visible. Combining this observation with the fact that the rib-tooling cladder was not disrupted led to the conclusion that the explosive had not sustained its detonation over the full length of the segment. This explosive failure, which is quite rare, was initially attributed to a crack or void in the explosive layer which had been generated during handling, but this presumption was disproved, as auxiliary experiments showed that voids or cracks of the size which might have been present were not capable of stopping the propagation of a detonation.

It was noted that the point at which the explosive failed corresponded to the location of one of the bands of solder. It was concluded that this solder band was higher than

49150

FIGURE 50. RIB-TOOLING AND SHELL COMPONENTS FOR NOZZLE WELDING EXPERIMENT

anticipated and extended into the explosive charge. When the rib-tooling cladder was placed onto the explosive charge and charge holder, the protrusion of solder displaced the explosive and reduced the thickness of the charge at this point. This reduction in thickness was evidently sufficient to terminate propagation of the detonation front.

The second experiment was assembled in a manner similar to the first. However, because of the problems encountered in the first welding shot, caution was taken in assembling and joining the rib-tooling components. Care was taken to insure that the solder layer was not excessively thick and would not interfere with the explosive detonation. In spite of these precautions; however, the assembly contained several gaps and the alignment between ribs and tooling was much less than desired. The components were explosively welded together, but the results were inconclusive. Some rib-to-shell welding had been achieved over the entire surface, but there were considerable areas of poor welding. This result was attributed to the poor alignment between the ribs and tooling.

Welding of Curved-Plate Ribs Using Confined Explosive

Because of the poor results obtained in the rib-to-shell nozzle-welding experiments, a series of experiments were run using the curved-component geometry employed earlier to examine a potential solution to the problem of welding ribs in a curved plate geometry. Three experiments were run to assess the value of confining the explosive charge in the area of maximum plate curvature.

In these experiments, rib-tooling cladder plates were used in place of the solid plates used earlier. These composite plates were prepared by placing the ribs and tooling in close lateral contact, fusion welding the ends of the ribs to hold them in alignment, and machining the resulting assembly to a height of 0.100 inch.

The rib-tooling component was then laminated with a matching 1/8-inch-thick stainless steel base plate and formed to the desired curvature. A 1/16-inch-thick steel spacer sheet was placed between the rib-tooling component and the base plate during forming to allow for the standoff gap required in the explosive-welding operation. Following forming, the stainless steel base plate was positioned on a concrete support anvil and the rib-tooling component was set at the desired 0.070-inch standoff gap from the base. A 1/8-inch-thick Neoprene rubber buffer was taped to the surface of the rib-tooling plate and a 9/16-inch-thick SWP-1 explosive charge was positioned on this buffer. The desired confinement of the explosive charge was provided by 1/16-inch-thick layers of lead sheet placed on the top surface of the explosive charge, and were located mainly over the curved portion of the plates. Several layers of lead were used to achieve the required confinement thickness.

In the first experiment, the general utility of this method was examined, and base and cladder plates were used that were bent to the truncated pyramidal shape used previously. The geometry was modified, however, to eliminate the sharp change in welding direction, and each of the angles was rounded to a radius of 1/2 inch. The lead-sheet confinement was placed over and slightly beyond the curved portions of the cladder. The total thickness of confinement used was 1/8 inch.

Following explosive welding, the steel tooling bars were removed by acid leaching to expose the rib-to-shell welds for examination. Sound welds had been produced over the full specimen, except for a 1/2-inch-long section of poor weld immediately downstream from the first curve. The rib-to-shell weld adjacent to the second curve was fully welded, however.

This experiment demonstrated the worth of the concept, which was then applied to the problem of welding to a curve similar to that in the nozzle (1-1/2-inch radius over approximately 120 degrees). In this second experiment, the configuration shown in Figure 51 was used. The explosive confinement was increased in thickness to 3/16 inch, and the length of the confinement sheets was increased to overlap both ends of the curve. In addition to these changes, the confinement was tapered at each end as shown.

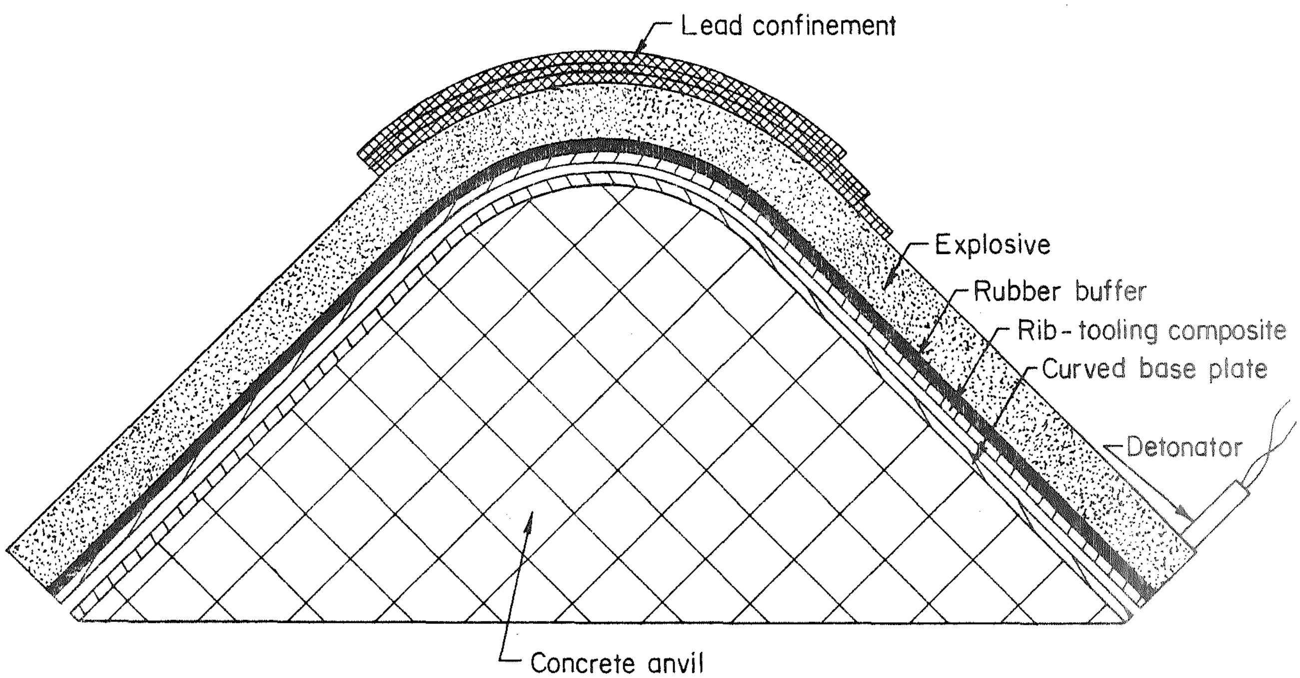


FIGURE 51. SETUP FOR EXPLOSIVELY WELDING RIBS TO A CURVED STAINLESS STEEL PLATE USING CONFINEMENT OF EXPLOSIVE OVER CURVED PORTION OF SPECIMEN

This experiment completely successful. Sound rib-to-shell welds were produced over the full length of the sample. This welded plate is shown on the right in Figure 52. It was noted upon examination that the surface of the stainless steel shell was severely disturbed (rippled) at the downstream side of the curve, and as a result, the confinement in this area was eliminated in the third experiment.

In the third experiment, this method was extended to the production of a complete shell-rib-liner curved plate. The liner-to-rib weld was made using flat-plate welding methods and was made prior to bending the plates for the rib-to-shell welding operation. The assembly used in the curved-plate welding operation was identical to that used in the previous experiment, except that the explosive was not confined at the downstream side of the curve beyond the point of tangency.

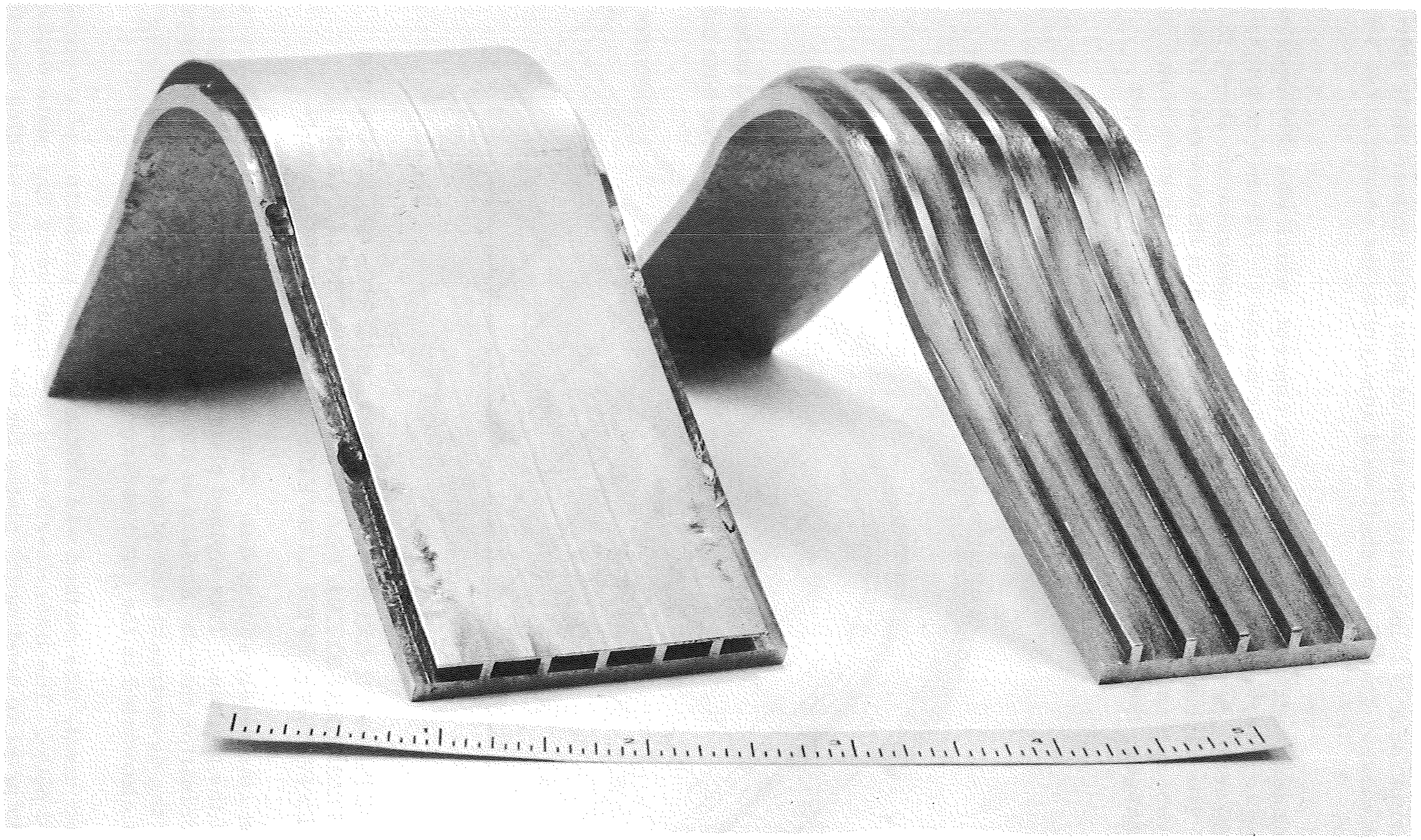


FIGURE 52. EXPLOSIVELY WELDED STAINLESS STEEL SAMPLES FROM CURVED PLATE-RIB EXPERIMENTS CR-2 (RIGHT) AND CR-3 (LEFT).

Specimen CR-3 also shows the explosively welded Hastelloy X liner.

Following welding, the mild-steel tooling was removed. The resultant structure is shown on the left in Figure 52. It was observed that both the rib-to-liner and the rib-to-shell welds were sound and continuous over the full length of the plates. One defect was found, however. The Hastelloy X liner had split along one side of the central rib in the curved section of the plate. This split was probably the result of a slight lateral spreading of the components during the second explosive-welding operation, and could be eliminated through use of a wider specimen.

SUMMARY OF RESULTS

The work done in this task of the program has shown that rocket-nozzle components can be readily fabricated by explosive-forming methods. Specifically, it was found that typical nozzle shells, having 3/8-inch-thick walls, minimum diameter of 6 inches, and maximum diameter of 13 inches, could be explosively formed from commercial-grade thick-walled pipe. This forming operation employed dieless forming to produce most of the contour, and formed the nozzles to final dimensions in a segmented thick-walled die.

It was also found that 70-degree segments of a complete nozzle could be explosively formed from flat stock in a single forming operation. Both thick (3/16 inch) and thin (0.020 inch) material could be formed to shape.

Preliminary welding experiments showed that discontinuous ribs – those which did not traverse the full length of the nozzle but terminated at the throat section – could be completely welded at each of the end terminations. Both ribs which "stopped" and those which "started" relative to the advancing detonation front could be welded through proper control of the shape of the adjacent mild-steel tooling.

Welding of plates curved in the direction of detonation was attempted and resulted, as expected, in areas of poor welding and large amounts of trapped melt between the plates. It was found that through use of either a slight longitudinal offset of the cladder plate or additional confinement of the explosive in the curved section, changed-direction welding could be achieved. As a specific demonstration of this capability, plates which had sharp 60-degree changes in welding direction were welded with no loss of welding over this angle.

It was found that welding of double-curved plates or ribbed sections was not as easily accomplished. The limited number of experiments performed did not permit an adequate solution to this problem to be developed.

CONCLUSIONS

Task I has shown that explosive welding can be used to reproducibly fabricate strong, sound, channeled flat-plate components. Two explosive-welding operations are required to produce panel specimens – the first yields a rib-to-shell weld, and the second produces a liner-to-rib weld. The rib-to-shell welding operation requires the use of an integral rib-and-tooling composite to achieve welds over the entire rib area. Mild steel has been found to be a satisfactory tooling material for this application. Liner-to-rib welds can be made using a conventional flat-plate explosive-welding operation. The channeled configuration is then achieved by removing the tooling with acid.

Task II has demonstrated that channeled spoolpieces (prototype cylindrical thrust chambers) can be fabricated by explosive welding. The welding operations required for fabrication of a complete spoolpiece are a rib-to-shell weld and a liner-to-rib weld, both on the bore of the chamber, and two end cover-to-plenum welds at each end of the chamber. It was found that adequate structural support must be provided for the spoolpiece components during the welding operation, and particularly during the rib-to-shell welding operation, when the greatest loadings occur.

Task III has resulted in a major advance in the art of explosive welding, and has demonstrated that explosive welding can be used to weld to surfaces curved in the direction of detonation. The objective of this task of the program – fabrication of a channeled nozzle segment – was only partially achieved, as a channeled, single-curved assembly was fabricated by explosive welding, but the double-curved nozzle segments were not completely weldable. Changed-direction welding methods were demonstrated, but their application to a specific practical problem (nozzle welding) was not successful because of secondary effects associated with the explosive's behavior and the component-assembly methods used.

RECOMMENDATIONS

It is recommended that additional work be undertaken to develop more fully the methods required to achieve reproducible changed-direction welding. This work should explore the fundamental mechanisms involved, but should also be oriented toward the practical problems of nozzle fabrication.

The study recommended here would best be performed in three phases. The first of these would involve examination of the kinetics of explosively accelerating curved plates through use of high-speed photographic and flash radiographic coverage. A study similar to the one suggested, but employing flat plates, has recently been completed, and the results are to be published*. This first phase would also involve examination of the detonation velocity and impulse produced by the explosive as the detonation front traversed the length of the nozzle. In the second phase of this recommended study, nozzle-shaped mock-up components would be employed to examine in detail the practicability of the solutions derived from the fundamental study and also suggested by the present work.

In the third phase, the solutions developed in the second phase work would be applied to the fabrication of ribbed nozzles. The scope of work would depend on the number and type of channeled nozzles required. If only several were needed, the most practical means of fabrication would be to mechanically or chemically machine the channels into a solid nozzle and then explosively weld a liner to the channeled structure. If many nozzles were required, it would be expeditious to fabricate them entirely by explosive welding. This approach would require the development of successful rib-welding methods.

*Smith, E. G., Jr., D. Laber, and V. D. Linse.

On the basis of the results of the present program, recommendations for fabricating much larger nozzles can be made. In these larger nozzles, the curvature would be less at any point, and as a result, the problems of precise control of the angularity of collision would be less. Stated another way, the problems associated with explosively welding the nozzles would be much less, and in fact, should be more amenable to solution than those inherent in the fabrication of smaller nozzles.

These larger nozzles would be fabricated in segments (perhaps 90-degree segments) and then joined on longitudinal seams by fusion welding. Depending on their size, dies of either mild steel or epoxy-faced concrete would be used as support for the shells during welding. The use of the latter material would mean that the required support dies could be fabricated easily and inexpensively, and still provide the required strength and support for the welding operation.

POTENTIAL APPLICATION TO OTHER AREAS

The explosive-welding technology developed in this program for the channeled thrust-chamber structure can be used to fabricate similar structures for many industrial applications. This technology can be applied with the view of developing new structures, improving existing ones, or simplifying their fabrication. Two examples of such structures are heat exchangers and high-strength, low-weight structural components. Both involve laminated or channeled structures which would utilize many of the techniques used for the thrust chamber. The explosive-welding process offers the following potential advantages relative to more conventional techniques for fabricating these structures:

(1) A wide selection of metals or combinations of metals can be welded into panel structures without the degradation of mechanical properties or reaction between the metals being welded.

(2) Potential to fabricate the structures in a variety of sizes and configurations.

(3) Size of panel structures is not limited by equipment.

(4) Capital equipment required for the process is minimal.

(5) Many other materials, in addition to steel, can be used for support tooling, including aluminum, low-melting-point alloys, salts, plaster, and plastics.

(6) Support anvils and dies can be fabricated from inexpensive construction materials such as concrete.

APPENDIX

ANALYSIS OF CHANGED-DIRECTION WELDING

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ANALYSIS OF CHANGED-DIRECTION WELDING

In the course of analyzing the cause of poor welding between longitudinally curved or angled plates, an analysis was made of the plate-collision conditions which existed for a particular angular geometry of plates being welded. The geometry analyzed had been used in several of the angled-plate welding experiments performed in Task III, and had resulted in several areas of nonwelding.

The component arrangement used is shown in Figure A-1. In this experiment, the upper stainless steel plate was separated initially from the mild-steel base component by a 0.060-inch gap, and the apices of the angles were positioned one above the other, i.e., no offset of the cladder plate was used.

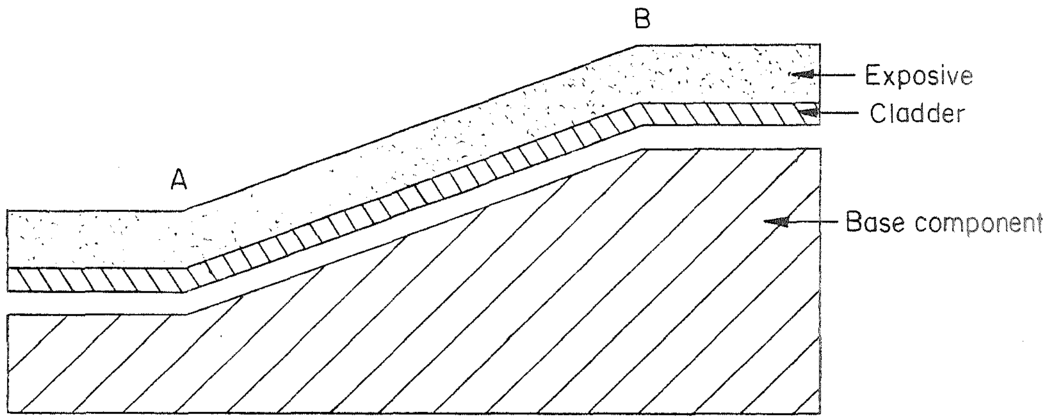
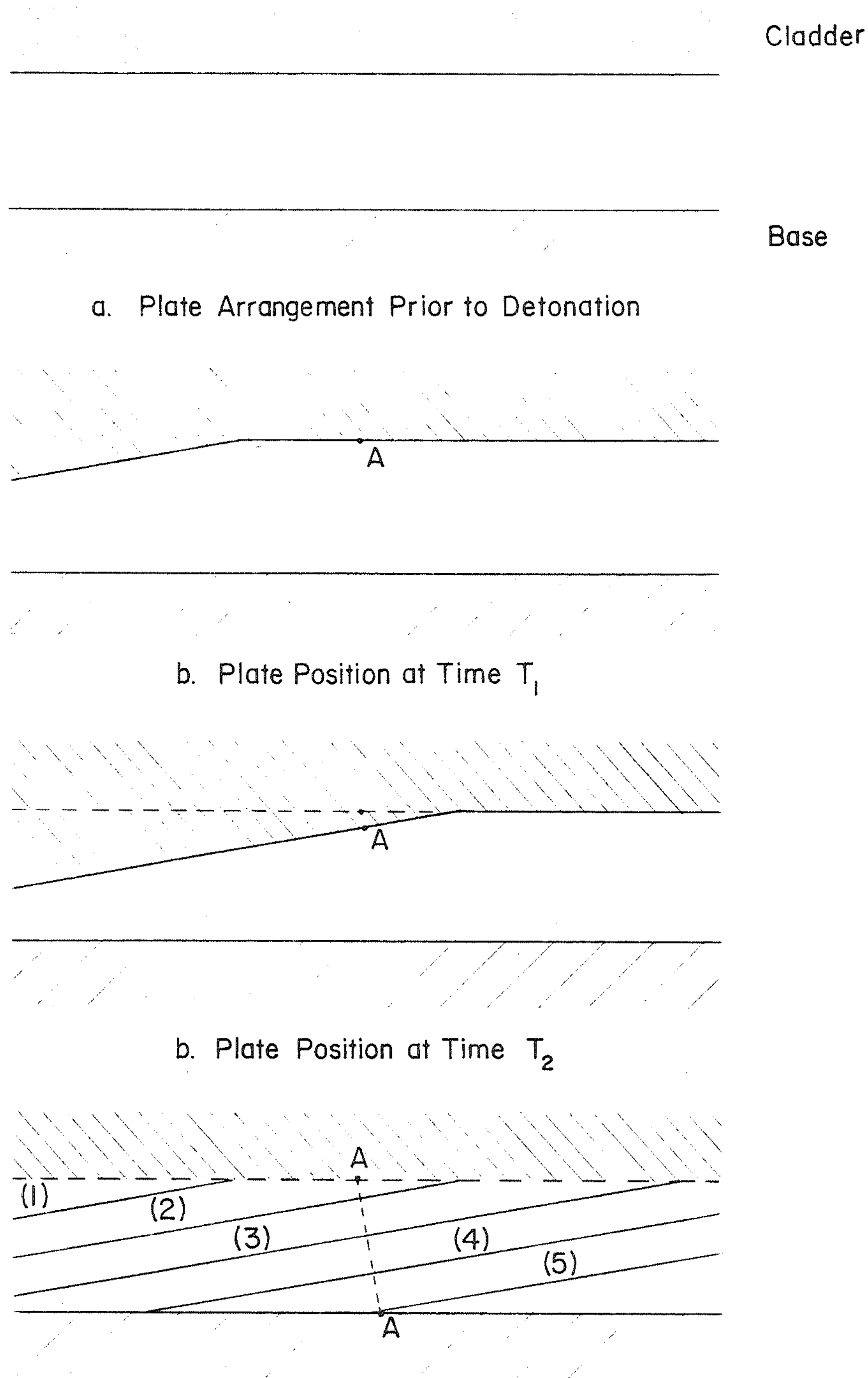


FIGURE A-1. EXPERIMENTAL ASSEMBLY FOR ANGLED-PLATE WELDING

Figure A-2 shows the basis for the method of analysis used in the following discussion. This figure shows the collision conditions between an accelerated cladder plate (top) and a base plate (bottom). For the sake of clarity, the cladder plate is shown as having reached its terminal velocity and angle instantaneously. (In reality the plate is accelerated in a stepwise manner and does not reach its maximum velocity until it has traversed a gap approximately equal to its thickness.) The angled lines designated (1), (2), etc., show the position of the cladder at several successive increments of time. The dashed line (AA') shows the path that a particle located on the initial stationary cladder (at A) takes during the motion of the plate as it is accelerated across tha gap and collides with the base. This diagram shows that a longitudinal displacement of the cladder occurs in the direction of detonation. This figure also shows that the collision angle remains constant at 8 degrees (the assumed bend angle achieved by the explosive loading used) for the full length of the experiment.

Figure A-3 shows the position of the cladder plate at several sequential points in time for one of the direction changes encountered in the angled-plate welding experiment.



a. Plate Arrangement Prior to Detonation

b. Plate Position at Time T_1

b. Plate Position at Time T_2

d. Composite Showing Plate Positions at Five Sequential Times

AA' shows the lateral motion of Point A.

FIGURE A-2. CLADDER PLATE MOTIONS RESULTING FROM EXPLOSIVE LOADING

Detonation moves from left to right.

This diagram has identified two adjacent points on the cladder plate, B and C. B is the last element on the horizontal surface of the cladder, and C is the first element on the inclined surface.

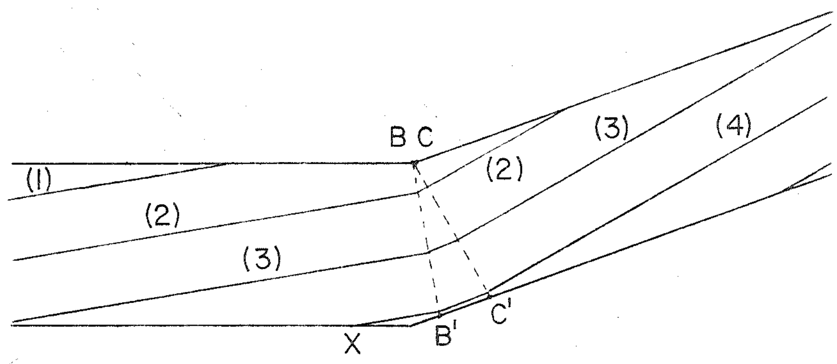


FIGURE A-3. COLLISION CONDITIONS WHICH EXIST AT THE BEGINNING OF AN INCLINE

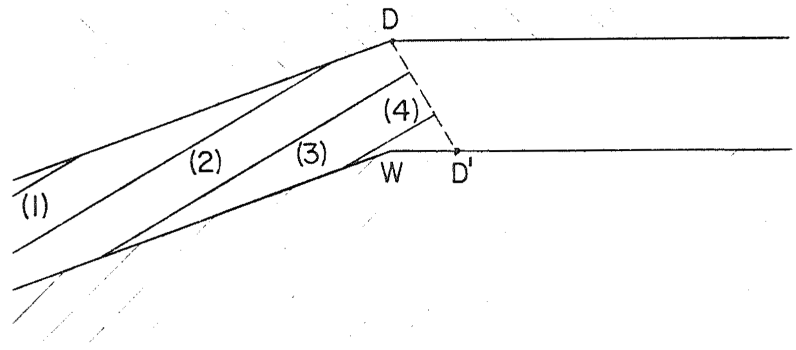
Two areas of nonideal collision conditions are produced, XB' and B'C'.

The diagram shows that at time T_4, collision conditions which produce poor welding exist over two areas of the base plate. The first of these areas, designated XB' in the figure, is a zone in which the high-energy jet produced by the metal-metal collision is trapped. A melt pocket results from this trapment. The second area, designated B'C' in the figure, is an area in which the collision angle is not sufficient to produce jetting (and therefore welding) and results in an area of poor or no welding. It should also be noted that the cladder plate stretches and thins out in this area. Both of the features predicted by the above analysis were observed in the actual experimental results.

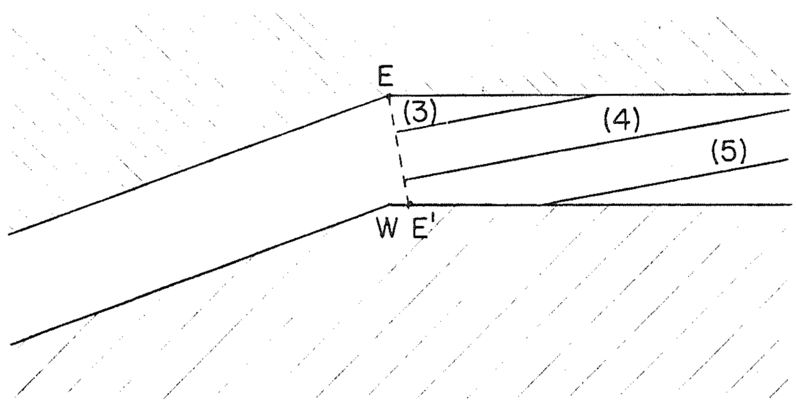
The same analysis was used to examine the details of the collision mechanics at the other angular transition located at the top of the slope. Figure A-4 shows the collision conditions which occur. Figure A-4a shows half of the plate collision – only that half of the cladder which initially was angled. Figure A-4b shows the other half – that half of the cladder which was horizontal initially, and Figure A-4c shows the composite of these two.

Again it can be noted that two areas show nonideal collision conditions. The area WD' exhibits a greater collision angle than does the surrounding area. While this greater angle results in larger waves in this area than in adjacent areas, it is otherwise not detrimental to good welding.

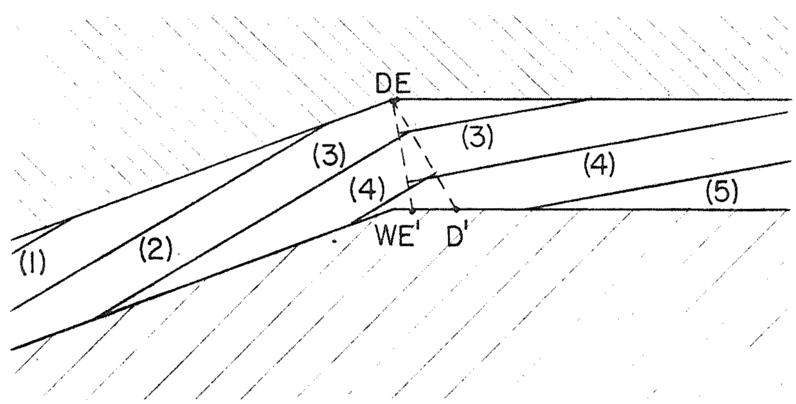
The other problem which can be noted in Figure A-4c is the overlap or "bunching up" of the cladder in the area E'D'. This phenomenon causes trapping of the jet and



a. Sequential Positions of the Initially Angled Cladder



b. Sequential Positions of the Initially Horizontial Cladder



c. Composite of a and b

FIGURE A-4. COLLISION CONDITIONS WHICH EXIST AT THE END OF AN INCLINE

Note the overlap of the cladder at E'D'.

results in a melt pocket. This overlap also results in a thickening of the cladder plate at this point. Both of these predicted results were in fact found in the welded plates.

These results suggested that a longitudinal offset of the cladder in the direction opposite to the detonation direction would be beneficial. An experiment was run to test this solution, and good welding was obtained over the full area of the angled plates.

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