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FINAL REPORT

DEVELOPMENT OF EXPLOSIVE WELDING PROCEDURES TO FABRICATE CHANNELED NOZZLE STRUCTURES

by

H. E. Pattee and V. D. Linse

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Prepared under Contract No. NAS1-13320 by

BATTELLE
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INTRODUCTION

Research was conducted by Battelle's Columbus Laboratories to demonstrate the feasibility of fabricating a large contoured structure with complex internal channeling by explosive welding procedures. The Langley Research Center has designed structures or nozzles of this nature for wind tunnel applications. Such nozzles vary widely in their complexity. However, in their simplest form, they consist of a grooved base section to which a cover sheet is attached to form a series of internal cooling passages. The cover sheet attachment can be accomplished in various ways: fusion welding, brazing, and diffusion welding. The cover sheet has also been electroformed in place. Of these fabrication methods, brazing has proved most successful in producing nozzles with complex contoured surfaces and a multiplicity of internal channels.

In previous work at Battelle, the feasibility of using explosive welding procedures to fabricate structures with internal channeling was demonstrated. While these structures were not as large, as severely contoured, or as complex internally as those contemplated in this program, it appeared likely that the explosive welding concepts could be extended to the fabrication of wind tunnel structures.

In contrast to other joining methods, explosive welding offers the following inherent advantages:

- Metallurgical joints can be produced between similar or dissimilar metals with almost equal facility.
- Joint strengths are commonly equal to or better than base metal strengths.
- Base metal properties are relatively unaffected by the joining operation since it is conducted at ambient temperature (some superficial melting of the surfaces

at the joint interface may occur but the effects of such melting are generally inconsequential).

- Welding over large surface areas can be accomplished in one operation; a multiplicity of rib-to-cover sheet joints can be also produced.
- Welding can be accomplished quickly with a minimum of facility and process requirements.

In recent years, explosive welding has advanced from a laboratory process to one that can be used in routine production operations, if the procedures are well developed and thoroughly evaluated (e.g., the cladding of sheet and plate stock, the repair welding of shafts, the production of flat and tubular transition joints, etc.).

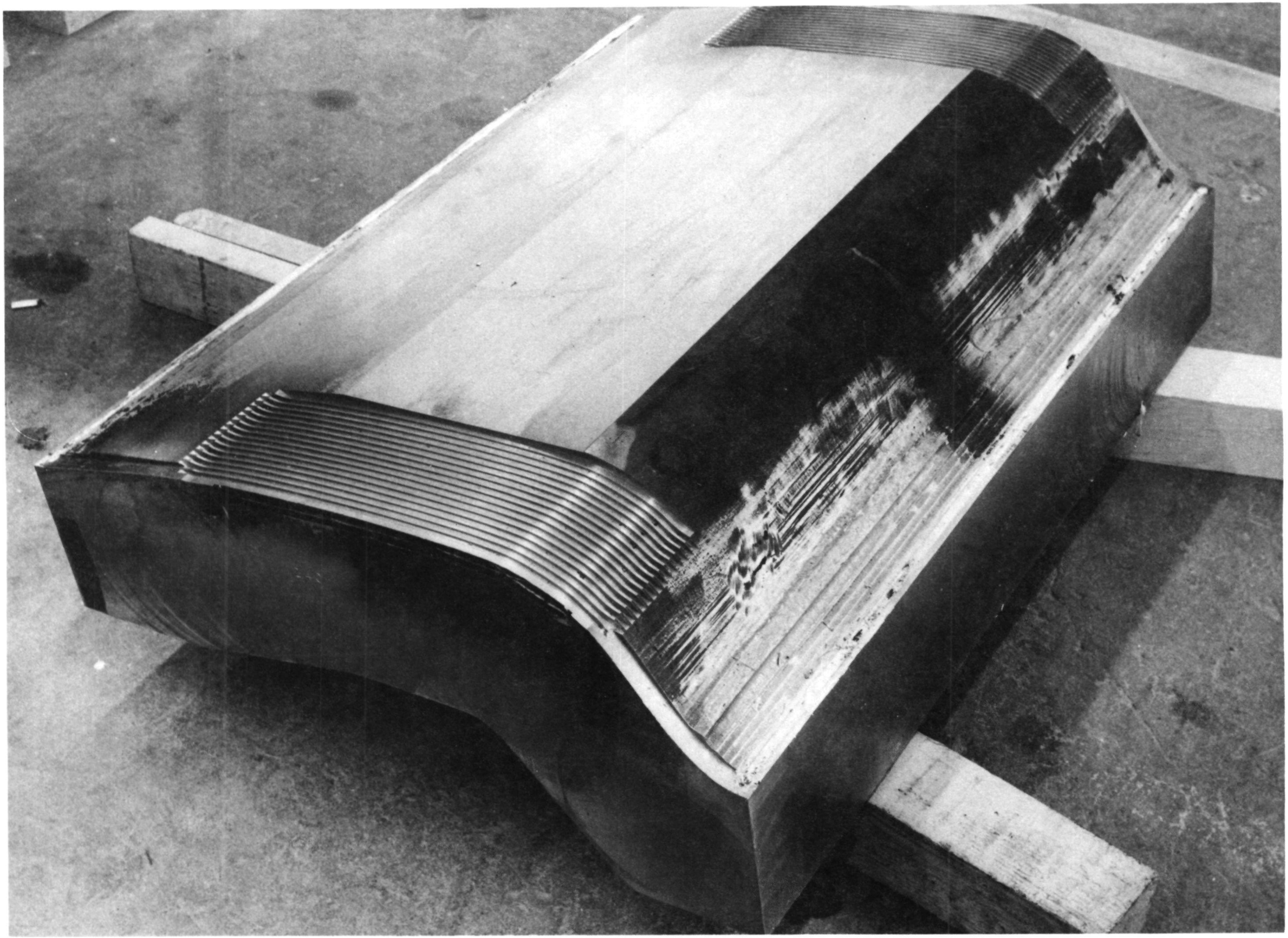
The structure to be considered during this program consisted of the following:

- Base. The base section was made from 405 stainless steel. The overall width and length of this member was about 25.8 and 36.0 inches, (65.5 and 91.4 cm), respectively; its height varied with the degree of surface contouring which ranged from a reverse curvature at the nozzle inlet to a fairly gentle curvature for much of the remaining surface. The contoured surface was machined to produce 120 channels, each 0.220 inch (0.56 cm) wide and each separated by a 0.063 inch (0.16 cm) wide rib. The base section is shown on the next page during machining (NASA Photograph L-73-1487).
- Cover Sheet. The cover sheet was made from 3/16 inch (0.16 cm) thick nickel. It was formed to match the contour of the base section.

RESEARCH PLANNING

The following two concepts for producing the required structure were considered:

- Curved Surface Approach. In this approach, the contoured cover sheet would be explosively welded to the contoured and channeled base section in one operation. This approach



NASA PHOTOGRAPH L-73-1487. BASE SECTION OF NOZZLE DURING MACHINING was simple; however, the development of procedures to weld over severely contoured surfaces would be required.

- Flat Plate Approach. In this approach, a flat cover sheet would be explosively welded to a flat, channeled base plate of the appropriate thickness; then, this welded assembly would be explosively formed to the proper contour. While this approach would simplify the explosive welding operation, forming would have to be accomplished without damaging the rib-to-cover sheet joints or distorting the cross section of the channels. However, the most negative aspect of this approach would be the expected difficulty in forming the thick-plate structure to the precise contours required for the nozzle.

Regardless of approach, the ribs would have to be supported with tooling in the channels.

At the start of the program, the first approach was adopted by mutual agreement between Battelle and Langley Research Center.

EXPERIMENTAL STUDIES

Welding Parameter and Tooling Selection

Welding Parameter Studies

The basic explosive welding conditions were established using a series of simple specimens that consisted of (1) a flat, ungrooved 304 SS* base section, 1 x 4 x 6 inches (2.5 x 10.2 x 15.2 cm), and (2) a pure nickel cladding plate 1/4 x 4 x 6 inches (0.63 x 10.2 x 15.2 cm). The explosive and its areal density were selected on the basis of prior experience. A nitrostarch-sensitized ammonium nitrate powder explosive (SWP-1)** which

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* Prior to the receipt of Type 405 stainless steel from NASA, Type 304 stainless steel was used for the base section because it was readily available at Battelle. Conditions for welding nickel to 304 SS were expected to be equally useful in welding nickel to 405 SS.

** SWP-1 explosive is manufactured by Trojan-U.S.Powder Company, Allentown, Pennsylvania.

detonates at a nominal velocity of 10,000 feet per second (3050 meters per second) was used. The manner in which the parts were arranged for welding is shown in Figure 1.

As indicated in Table 1, optimum welding was achieved in specimens welded with SWP-1 explosive (1.98 g/cm^2 density) at standoff distances of 1/8 inch (0.32 cm) and 3/16 inch (0.48 cm). The results obtained with these specimens are discussed below:

Specimen 3-1. This specimen was welded with a standoff distance of 1/8 inch. Except for a short section at the detonation end of the specimen, the weld was continuous for the length of the plate. There was a series of discontinuous melt pockets along the joint interface; some shrinkage voids were present in the melt pockets. A typical joint section is shown in Figure 2a.

Specimen 3-2. This specimen was welded with a standoff distance of 3/16 inch. The appearance and quality of this joint was similar to that associated with Specimen 3-1. Again, discontinuous but slightly heavier melt pockets were present along the interface. A typical microstructure is shown in Figure 2b.

The results of this investigation indicated that a 1/4-inch-thick nickel cover plate could be successfully welded to a flat, unchanneled 304 SS base section using SWP-1 explosive (1.98 g/cm^2) and standoff distances of 1/8 or 3/16 inch. Similar experiments were conducted with channeled base sections; these studies are reported in the section concerned with tooling selection.

Selection of Channel Tooling

The fabrication of channeled structures requires strong, consistent rib-to-cover sheet joints. To achieve this objective without damaging the ribs or significantly changing the channel cross section, the ribs must be supported during welding. Support tooling requirements are indicated below:

TABLE 1. EXPERIMENTAL SPECIMENS FOR EXPLOSIVE WELDING

Specimen No.[1]	Specimen Type	Cladder		Base		Welding Conditions			Discussed on Page No.
		Thickness, in.	Material	Thickness, in.	Material	Explosive	Density, g/cm²	Standoff	
3-1	Flat Plate	1/4	Nickel	1	304 S.S.	SWP-1[2]	1.98	1/8	5
3-2	"	1/4	"	1	304 S.S.	"	1.98	3/16	5
3-3	"	1/4	"	1	304 S.S.[3]	"	1.98	1/8	10
3-4	"	1/4	"	1	304 S.S.[3]	"	1.98	1/8	10
4-1	"	1/4	"	1	405 S.S.[3]	"	1.98	3/16	12
4-2	"	1/4	"	1	405 S.S.[3]	"	1.98	3/16	14
CV-1	Convex	1/8	304 S.S.	1/4	304 S.S.	"	1.32	1/8	17
CC-0	Concave	3/16	304 S.S.	1/4	304 S.S.	"	1.65	1/8	23
CC-1	Concave	3/16	304 S.S.	1/4	304 S.S.	"	1.65	1/8 to 1/4	23
CCV-1	Convex-Concave	3/16	304 S.S.	1/4	304 S.S.	"	1.65	1/8 to 5/16	28
CCV-2	Convex-Concave	3/16	304 S.S.	1/4	304 S.S.	"	1.65	1/8 to 1/4	30
CCV-3	Convex-Concave	3/16	304 S.S.	3/8	304 S.S.[3]	"	1.65	1/8 to 1/4	35
CCV-4	Convex-Concave	3/16	304 S.S.	3/8	304 S.S.[3]	"	1.65	1/8 to 1/4	38
CCV-5	Convex-Concave	0.040	Nickel	3/8	405 S.S.[3]	"	1.32	0.080-0.100	41

(1) Only numbered specimens included in table; other unnumbered specimens are discussed in text.
(2) SWP-1 explosive: a nitro starch-sensitized ammonium nitrate powder explosive made by Trojan-U.S. Powder Company
(3) Channeled base plate.

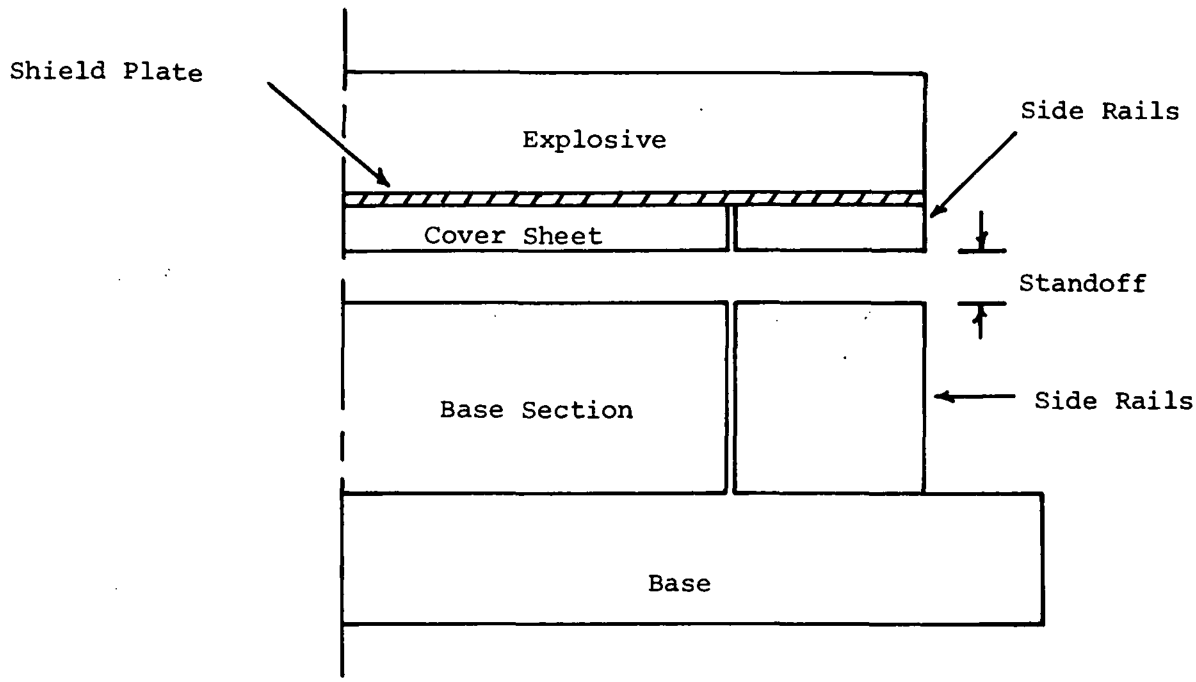
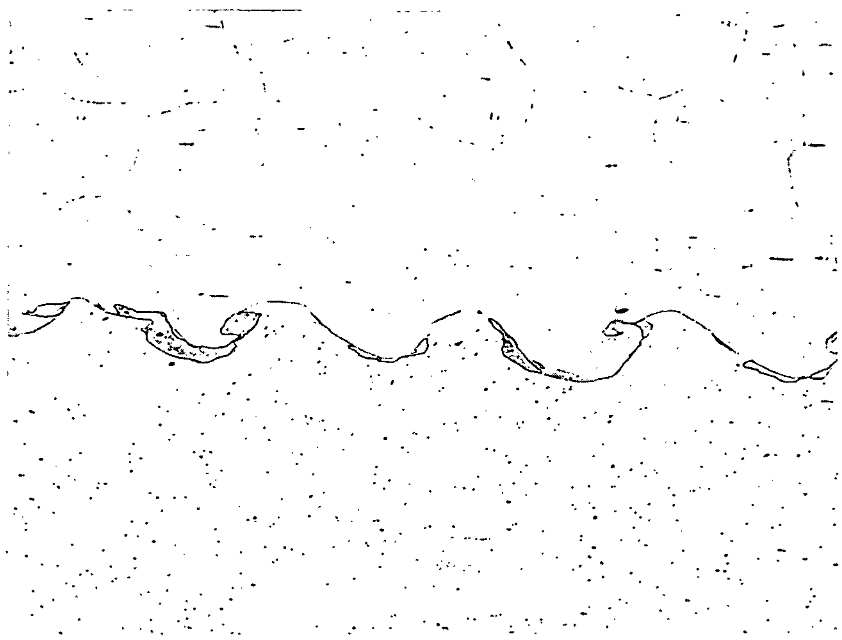
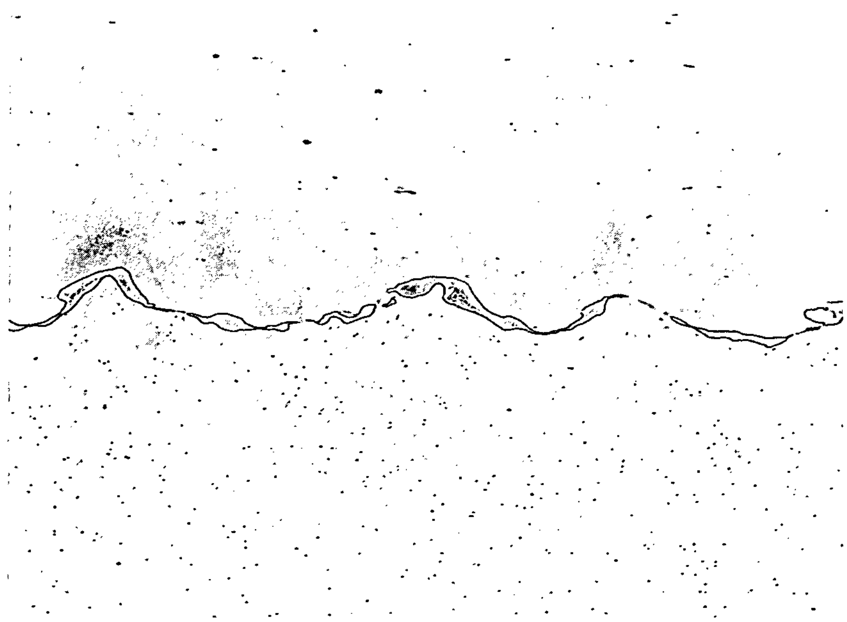


FIGURE 1. ARRANGEMENT OF PARTS FOR EXPLOSIVE WELDING



100X 1H398

a. Standoff distance: 1/8 inch (3-1)



100X 1H408

b. Standoff distance: 3/16 inch (3-2)

FIGURE 2. MICROSTRUCTURES IN EXPLOSIVELY WELDED JOINTS BETWEEN NICKEL AND 304 SS

- Easily installable in the channels
- Easily and completely removable from the channels after welding
- Strong enough to provide the required support
- Compatible with the base metals.

In many instances, a material (steel, copper, etc.) that can be removed from the channels by acid leaching is used to support the ribs during welding. Such materials were unsuitable for this application because the base metals (405 SS and nickel) as well as the support tooling would be leached by the acid. Thus, studies were initiated to select a low-melting alloy that would provide the needed support while meeting the other requirements noted above.

The following support tooling materials were considered and evaluated:

- Bi-26.7Pb-13.3Sn-10Cd (mp = 70 C or 158 F)
- Zinc (mp = 419 C or 786 F)
- Bi-42Sn (mp = 138 C or 280 F).

On the basis of melting temperature alone, it appeared that the bismuth-base alloys could be easily installed and removed from the channels; however, they might not provide the required support. Zinc appeared better from the support standpoint but problems might be encountered in installing and removing this metal from the channels.

The effectiveness of Bi-26.7Pb-13.3Sn-10Cd and pure zinc as channel support tooling materials was determined using a series of speciments with the same overall dimensions as those used to establish the basic explosive welding parameters. For these studies, a series of grooves was milled in the 304 SS base section. The grooves were 0.187 inch (0.48 cm) wide and 0.100 inch (0.25 cm) deep; the ribs separating the grooves were 0.0625 inch (0.16 cm) wide. The following steps were used to install the support tooling:

- Fill grooves with molten support tooling material.
- Grind base section to remove surface irregularities and to expose the land or rib surface.
- Undercut tooling in grooves 0.005 inch (0.01 cm) below the land or rib surface.

- Electrolytically deposit 0.005 inch (0.01 cm) nickel over base section surface.
- Grind base section surface to remove nickel plating from the rib welding surface.

Nickel plating of the tooling is required to prevent jetting and sweeping any of this material into the joint area during welding.

The parts were arranged for welding as indicated in Figure 1. Welding was done with SWP-1 explosive (1.98 g/cm^2) at a standoff distance of 1/8 inch (0.32 cm). The results of these studies are discussed below:

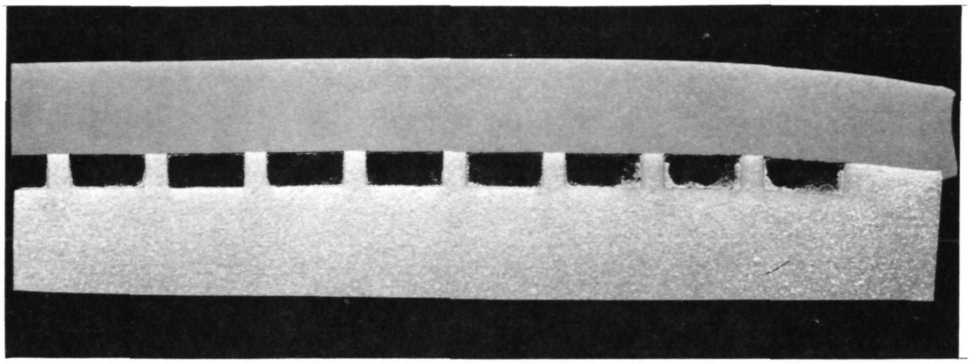
Zinc Tooling (3-3). After welding, the specimens were heated to about 800 F to melt the zinc tooling. Some of the molten zinc flowed from the channels; the remainder was forced from the channels with a small rod. Apparently, the presence of an oxide film prevented the free flow of the tooling material.

Longitudinal and transverse sections of the specimens were examined. Excellent welding was produced. The joint microstructure was similar to that observed in Specimen 3-1; however, the wave pattern was somewhat more irregular. Discontinuous melt pockets were present along the joint interface, but there was no evidence that any of the tooling material had been swept into the joint during welding.

In the transverse section (Figure 3a), the almost rectangular shape of the ribs indicated that adequate support was provided by the zinc tooling. However, the presence of zinc in the channel corners indicated the difficulty with which the tooling was removed.

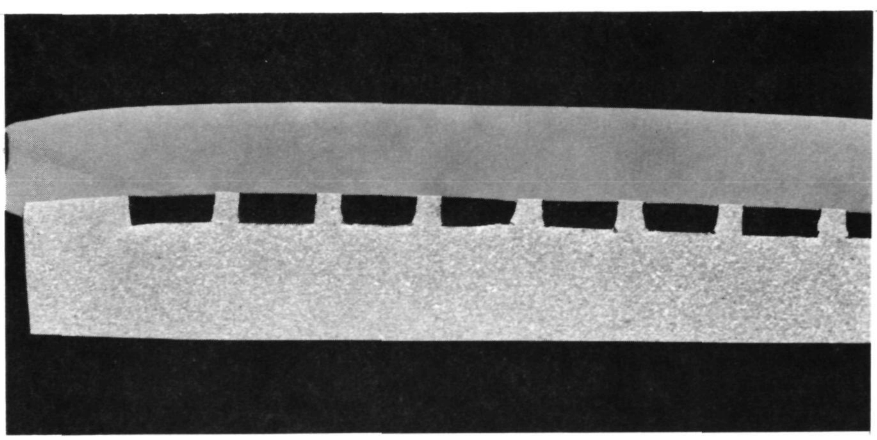
Bi-26.7Pb-13.3Sn-10Cd Tooling (3-4). The tooling was removed easily from these specimens. Much of it flowed from the channels upon becoming molten; the remainder was removed with a compressed air blast through the channels.

Again, longitudinal and transverse sections of these specimens were examined. Excellent welding was produced and the joint microstructure was similar to that observed in Specimen 3-3. There was no evidence of tooling in the joint area.



2X 1H527

a. Zn Support Tooling (3-3)



2X 1H526

b. Bi-26Pb-13.3Sn-10Cd Support Tooling (3-4)

FIGURE 3. EXPLOSIVE WELDED NICKEL TO 304 SS JOINTS MADE WITH VARIOUS SUPPORT TOOLING MATERIALS

The distorted shape of the ribs (Figure 3b) indicated that the support provided by the bismuth tooling was less than adequate. However, there was some evidence that this tooling material did not conform to the precise contours of the channel, particularly in the corners, because of poor wetting to the stainless steel. Then, the intense pressures created during explosive welding resulted in deformation of both the tooling and the ribs into these void areas.

Thus, while the zinc tooling provided better support than the bismuth-base alloy, it was extremely difficult to remove completely from the channels; more serious problems in tooling removal could be anticipated with the full-scale contoured nozzle. The bismuth-base alloy was easy to remove from the channels, but it did not appear to provide the required support because of difficulties associated with filling the channels completely. Therefore, additional studies of tooling materials were conducted.

Since the bismuth-base alloys appeared promising because of ease of removal, another alloy of this type (Bi-42Sn) was included in this investigation. This alloy melts at 138 C (280 F) and reportedly reproduces fine details better during casting than Bi-26.7Pb -13.3Sn-10Cd. The evaluation of this support tooling material was combined with studies to establish the basic explosive welding parameters for joining nickel to 405 SS, the materials used in the full-scale nozzle. In this instance, the specimens consisted of (1) a flat, channeled 405 SS base section, and (2) a pure nickel cover plate. The design of the channeled base section is shown in Figure 4; the channels were manifolded to facilitate removal of the support tooling with a compressed air blast.

After machining, the channels were filled with the support tooling in the manner described previously. Then, the parts were arranged for welding as shown in Figure 1. Two specimens, 6 and 12 inches (15.2 and 30.4 cm) long were welded using the following parameters: SWP-1 (1.98 g/cm^2) and a standoff distance of 3/16 inch (0.48 cm). After welding, the specimens were heated to melt the support tooling which was then removed from the channels with a compressed air blast. Each specimen was sectioned to produce a longitudinal and transverse sample.

<u>Specimen 4-1 (Bi-42Sn)</u>. Metallographic studies of the 6-inch-long specimen indicated that the nickel cover plate was well

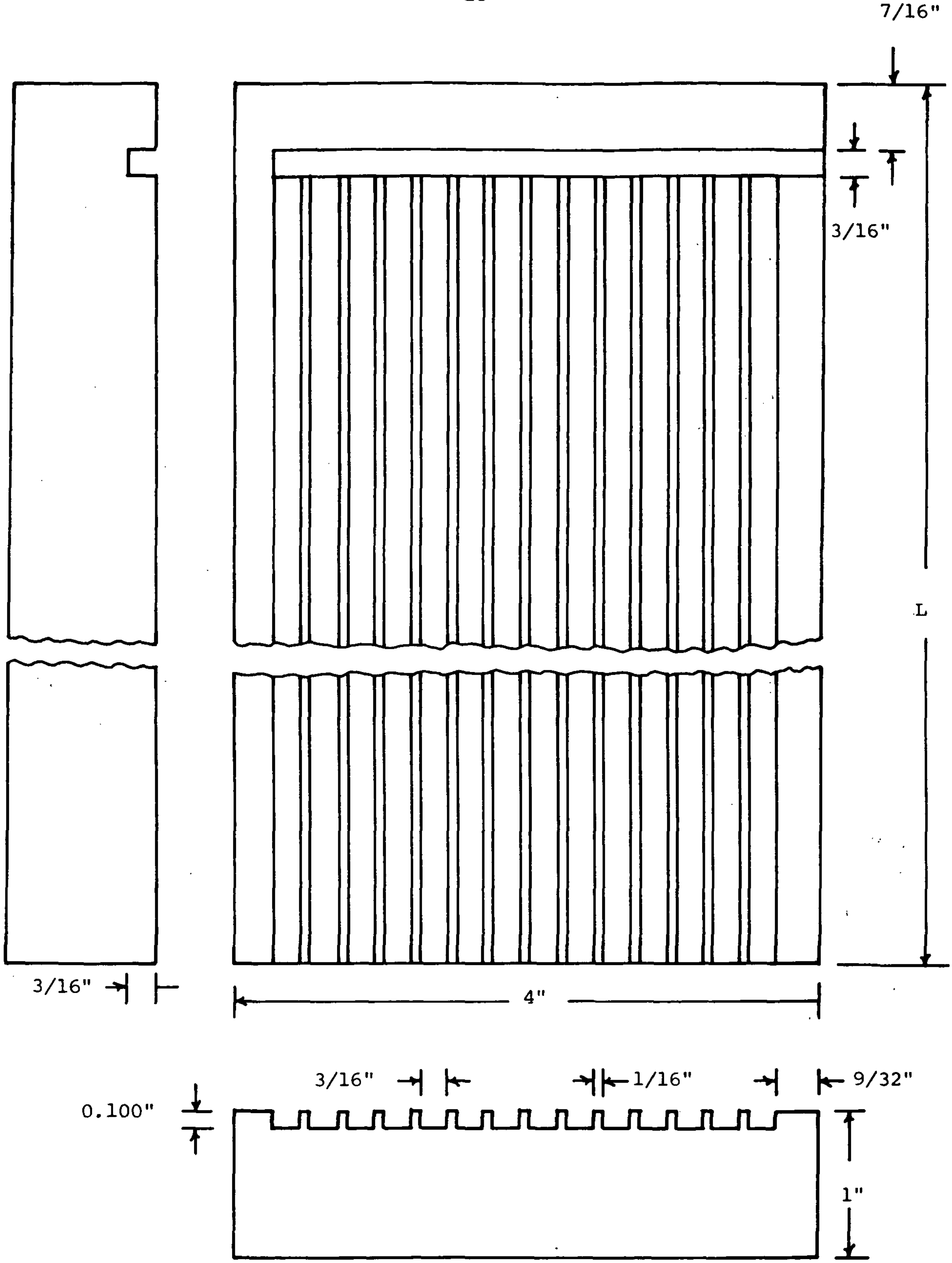


FIGURE 4. DESIGN OF 405 SS CHANNELED BASE SECTION

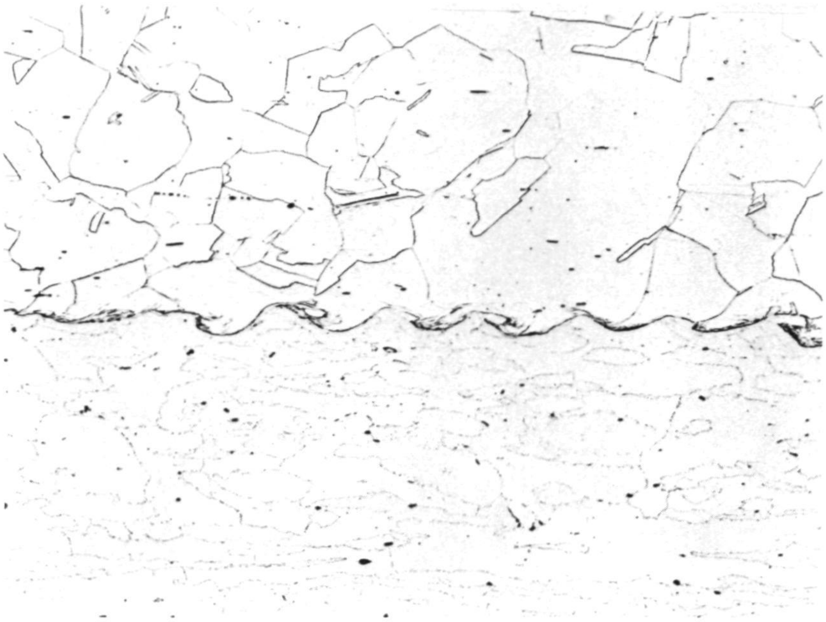
bonded to the 405 SS base section; there was no evidence that any of the support tooling had been swept into the joint area during welding. A photomicrograph of a typical area along the joint interface is shown in Figure 5a. Typically, discontinuous melt pockets were present along the joint interface and there were some isolated shrinkage voids.

An examination of the transverse section (Figure 5b) indicated that the Bi-42Sn tooling provided much improved support to the ribs during welding; apparently this material conformed much better to the channel cross section during installation. The sides of the ribs remained essentially vertical and very little support tooling was present in the channels.

Specimen 4-2 (Bi-42Sn). Sections from the 12-inch-long specimen were also examined. It appeared that a relatively long section could be welded as easily as a short one, because there was essentially no difference in the metallurgical characteristics of these joints and the joints in Specimen 4-1. Also, the tooling was removed easily from the channels.

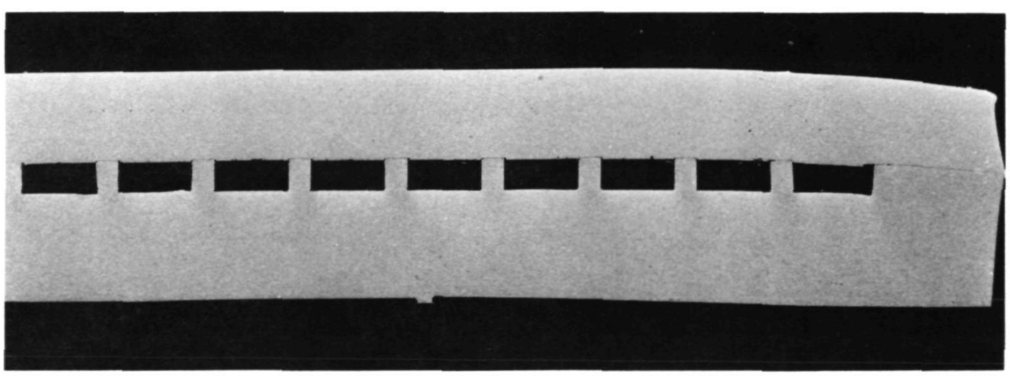
The steps required to install the channel support tooling and prepare the base section for welding have already been cited. While individual operations (e.g., undercutting, surfacing, etc.) could be readily accomplished with a flat, channeled assembly, it would be much more difficult and time consuming to accomplish them with a contoured, channeled assembly. Limited studies were conducted to evaluate possible techniques for simplifying these procedures.

- The casting of Bi-42Sn strips for subsequent insertion in the channels was considered and several strips were cast into a small mold. However, this approach appeared impractical because the strips had to be cast undersize for easy insertion in the channels. Such strips would not provide adequate support for the ribs because they would attempt to conform to the precise shape of the channel during welding and would be deformed as a result. Also, the machining tolerances on the channels of the full-scale assembly rendered this approach unsuitable.



100X 1H634

a. Longitudinal Section



2X 1H654

b. Transverse Section

FIGURE 5. EXPLOSIVELY WELDED NICKEL TO 405 SS JOINT MADE WITH Bi-42Sn CHANNEL TOOLING

(Made with Bi-42Sn support tooling)

- To eliminate undercutting of the tooling, studies were conducted to develop an acid leaching method for removing a thin (0.005 inch thick) layer of the tooling material in preparation for electroplating. Such a procedure was developed, but the amount of tooling removed could not be controlled. Also, some constituents of the tooling material were preferentially etched due to the metallurgical inhomogeneity of the cast tooling structure.
- Attempts were made to protect the surface of the support tooling with nickel foil strips to eliminate the need for electroplating. This proved to be impractical because the strips did not prevent jetting of some tooling material into the joint during welding.
- In order to eliminate the need to remove the nickel plating and expose the welding surfaces of the ribs following plating, studies of various materials were conducted to select a method for protecting the rib surfaces during electroplating. An electroplating stop-off material was found to provide adequate protection, thus reducing the time required to clean up and expose the rib surfaces in preparation for welding.

Discussion of Results

The results of these preliminary flat-plate studies indicated that satisfactory rib-to-cover sheet welds could be produced using the following parameters:

Explosive	SWP-1
Explosive loading	1.98 g/cm^2
Standoff distance	1/8 to 3/16 inch.

The best support for the ribs during the welding operation was found to be low-melting point Bi-42Sn alloy cast into the channels and covered with a 0.005-inch-thick layer of nickel plating on the exposed surface. With the proper care, this alloy can be cast to conform well to the complex shape of the channels in the full-scale nozzle. The alloy can then be easily and completely removed following welding.

Welding of Unchanneled-Curved Assemblies

Studies were next directed toward adjusting the explosive-welding parameters and developing the procedures for welding curved sections with contours essentially the same as the LRC nozzle. These studies were conducted with unchanneled components.

One of the most important requirements for achieving a sound explosive weld over a large surface area such as the LRC nozzle, is the maintenance of uniform or steady-state collision conditions between the cladding and base section components over the entire weld surface. This is easily accomplished on a flat-plate structure where the egress of the welding front is in a straight line. However, when explosive welding over a contoured or curved surface, it becomes inherently more difficult to maintain these steady-state collision conditions and obtain uniform welding. It then becomes necessary to adjust the welding parameters and apply special welding techniques to accommodate the effects of the curvature. This is particularly necessary in regions of the nozzle where the curvature is severe.

To prepare specimen components for these welding studies with the same contour as the nozzle, the precise contours of the finish, land, and channel surfaces of the nozzle were plotted with the aid of a simple computer program and the X-Y coordinate data provided on NASA Drawing No. LD-523 892. These plotted contours were then used to fabricate the contoured components. Experiments were initially conducted to individually study the two areas of the nozzle that would present the most difficulty in welding: i.e., the convex and concave regions. The final experiments then combined these two regions into a single convex-concave specimen or component to evaluate the effects of these two regions on each other during welding. The results of these experiments are discussed in the following sections.

Convex Welding "Segment CV-1"

When detonating over a convex surface, the detonation front in an explosive layer has a tendency to egress in a straight line or off the surface into space. This can be somewhat compared to an inertial effect. Although the explosive does sustain its detonation over the convex surface, the impulse which it delivers to the cladding component (cover plate) is greatly reduced; in turn, this results in reduced collision energy and loss of welding in this area. A second effect of convex welding is the thickening or gathering of the cladding component (cover plate) in the most severely contoured area. This thickening or gathering also contributes to a poor quality weld in the convex region. These welding experiments were therefore directed toward adjusting the welding parameters and procedures to eliminate the effects of these two phenomena and produce a uniform weld over the entire convex region.

The components for the convex experiments consisted of (1) a 1/8-inch-thick (0.32 cm thick) 304 SS cover sheet, and (2) a 1/4-inch-thick (0.64 cm thick) 304 ss base section. Both plates were formed in a press brake to reproduce the convex contour of the nozzle land surface. The forward end of the segment was lengthened slightly to permit stabilization of the explosive wave after passage through the curved area. The entire assembly was 12 inches (30.5 cm) wide by 13 inches (33.0 cm) long.

The base section was imbedded in a concrete base that provided support to the convex segment during welding. Then, the parts were assembled as indicated in Figure 6 with a standoff distance of 1/8 inch (0.32 cm). Lead sheet was placed on the top or exposed surface of the explosive over the most pronounced area of curvature to control the uniformity and direction of the welding forces; the area tamped with lead was about 5 inches (12.7 cm) long. To determine tamping needs, experiments were conducted with lead sheet tamping thicknesses ranging from 1/8-inch-thick (0.32 cm thick) to 3/16-inch-thick (0.48 cm thick). Welding was done with SWP-1 explosive at an areal loading of 1.32 g/cm^2. The direction of welding is shown in Figure 6.

The convex segments were successfully welded in all cases. The contours were in general conformance with that of the full-scale nozzle except where welding was initiated. Deformation in this area occurred because of insufficient support provided by the concrete base at the front or leading end of the setup.

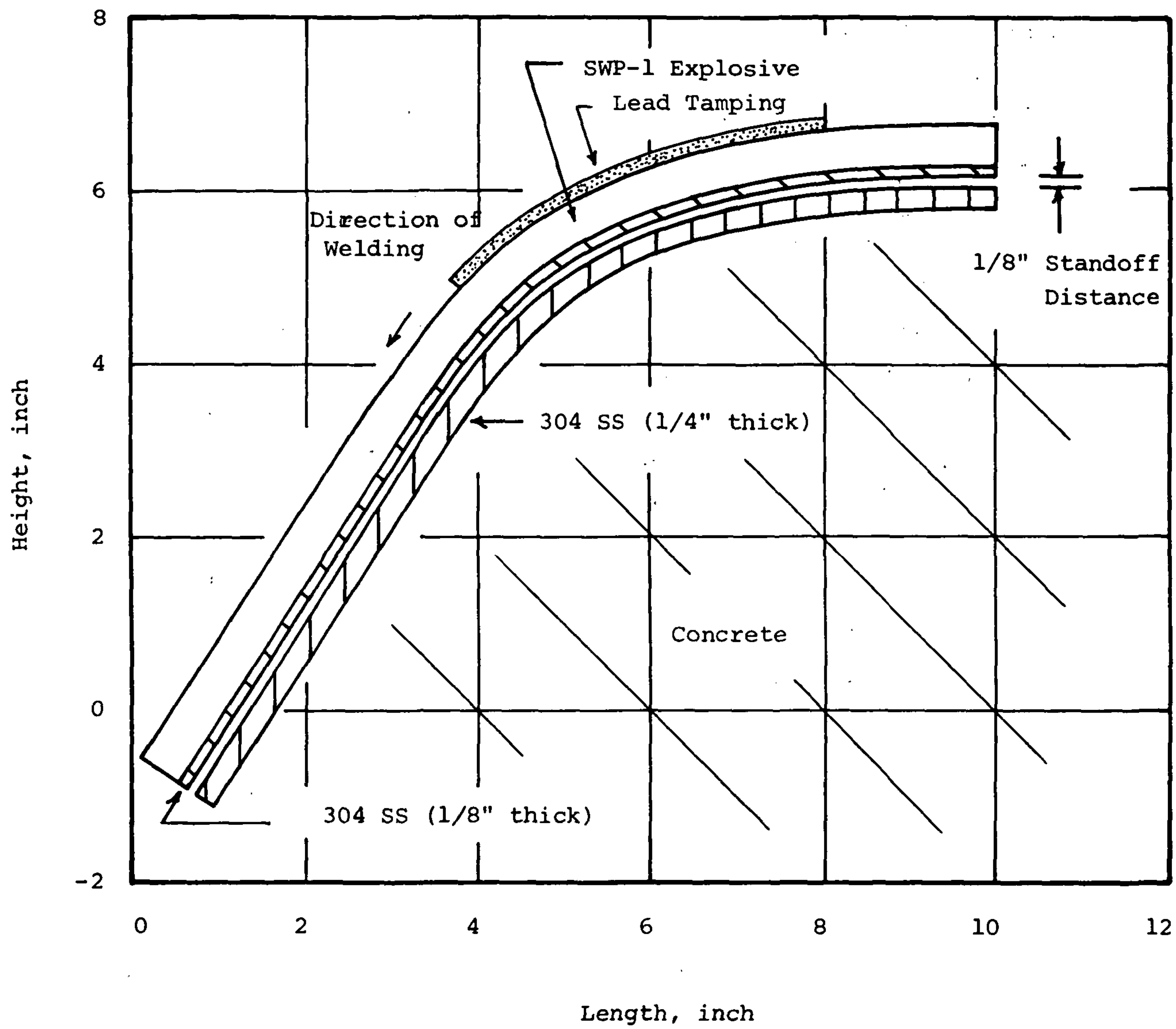


FIGURE 6. EXPLOSIVE WELDING OF UNCHANNELED CONVEX NOZZLE SEGMENT

The weldments were cut to produce sections parallel to the direction of welding. Visual inspection indicated complete joint integrity except for the expected short, unbounded areas at the start and finish of welding. Metallographic sections from areas tamped with 1/8-inch-thick lead (Sections CV-1A-1 through CV-1A-3) and 3/16-inch-thick lead (Section CV-1B-1) were examined with the following results (see Figure 6 for location of sections):

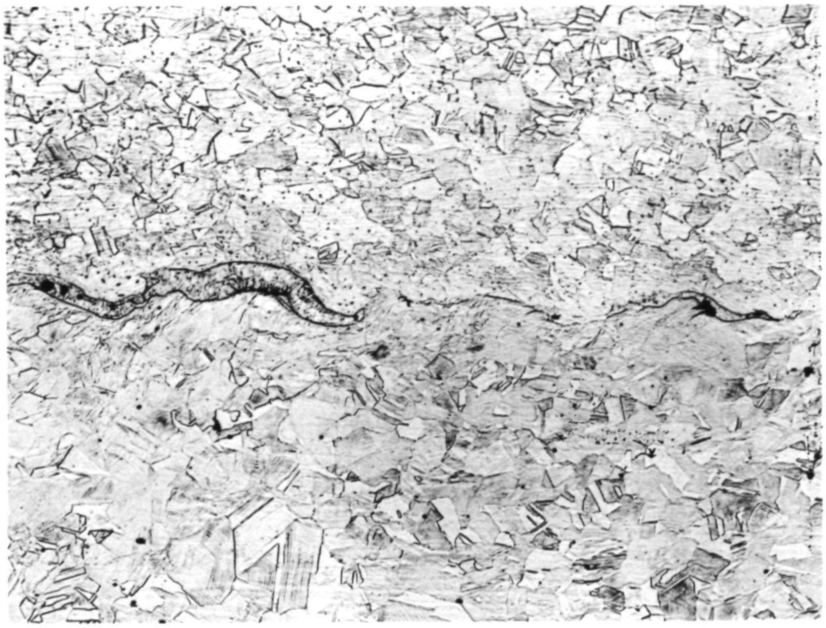
Section CV-1A-1. This section was located about 2 inches (5 cm) from the initiation of welding. The wave pattern that is characteristic of explosive welding was evident at the start of welding. There were some discontinuous melt pockets along the interface with some isolated shrinkage pores. As welding progressed into the curvature, the size of the melt pockets increased until a continuous phase was formed (Figure 7a).

Section CV-1A-2. This section was located in the most pronounced area of curvature. Here, there was an almost continuous phase along the interface where superficial surface melting occurred during welding (Figure 7b).

Section CV-1A-3. This section was located about 1-1/2 inches (4.2 cm) from the trailing end of the weld. Again, there was a more or less continuous series of melt pockets along the joint interface. The occurrence of melt pockets decreased as welding progressed and, finally, ceased as the welding conditions stabilized.

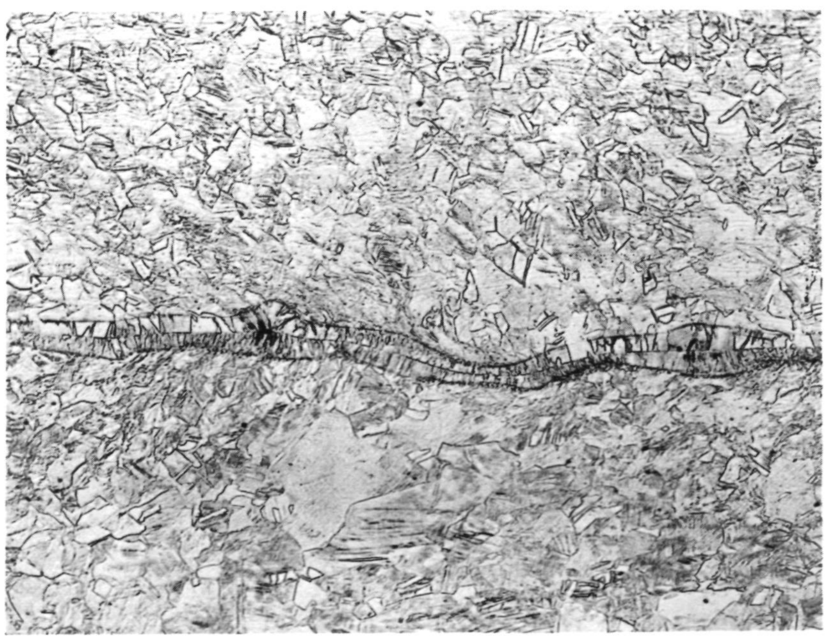
Section CV-1B-1. This section was located in an area where increased lead tamping was present; the specific location was in the area of most pronounced curvature. The microstructure was similar to that observed in Section CV-1A-2 except that the width of the continuous phase was slightly larger.

These studies indicated that the explosive welding parameters employed would produce a continuous weld over the entire length of the convex region; however, the welds in the region of maximum curvature



100X 10% Chromic Electro-Etch 1H866

a. Section CV-1A-1 (located near initiation end)



100X 10% Chromic Electro-Etch 1H867

b. Section CV-1A-2 (located in convex curvature)

FIGURE 7. JOINT MICROSTRUCTURES IN CONVEX SEGMENT

($1.33\ g/cm^2$ SWP-1 explosive; 0.32 cm standoff distance) were not quite as uniform as desired. It appeared, however, that a slight reduction in the standoff distance in this region in the subsequent convex-concave experiments would improve the weld quality. The experiments also showed that the thinnest lead tamping (1/8 inch) was sufficient in the convex region.

Concave Welding

As discussed previously with convex welding, a directionality of the detonating explosive also exists in concave welding. In concave welding, however, this directionality is opposite to that in convex welding because the detonation tends to head into the cladding component (cover plate) in the region of most severe curvature. This results in loss of the required collision conditions (particularly, the collision angle) and a subsequent loss of welding. It was expected that this effect could be countered by gradually increasing the standoff distance as welding progressed through the concave region.

A second effect was also expected in the concave region. In contrast to the thickening or gathering of the cover plate experienced in the convex region, the cover plate would be stretched and thinned in the concave region. This would leave some tensile stresses in the weld in this region. If the weld quality in the concave region was marginal, these residual stresses would in all probability fracture the weld immediately following welding. No adjustment in the welding parameters or procedures except those leading toward the production of a high-quality weld in the concave region could be made to counter this effect.

A series of concave welding experiments was conducted to establish the parameters and procedures required to produce a sound weld through this region of the nozzle. In these experiments, the major variable investigated was the effect of standoff distance in the concave region on weld quality. The results of these experiments are discussed below.

Uniform Standoff Distance "Segment CC-0"

This segment consisted of (1) a 3/16-inch-thick (0.48 cm thick) 304 SS cover sheet, and (2) a 1/4-inch-thick (0.64 cm thick) 304 SS base section. The joint members were press-brake formed to produce the concave curvature of the nozzle land surface. The overall size of the weldment was about 12 inches (30.5 cm) wide and 11 inches (28.0 cm) long.

After the base section was cast into a concrete base, the parts were assembled to produce a constant standoff distance of 1/8 inch (0.32 cm) as indicated in Figure 8. Welding was done with SWP-1 explosive at a loading of 1.65 g/cm^2.

As expected, this segment was not completely welded over its entire length. Following the typical, short unbonded region at the initiation end, welding was established and continued until the concave region of the specimen was reached. In the concave region, excessive surface melting occurred and the resultant weld was fractured and the components were separated in this region. The observed deformation in the specimen following welding also indicated that rigid support by the concrete support base in the concave region was essential.

Variable Standoff Distance "Segment CC-1"

The workpieces for this segment were prepared in the same manner as those for the previous segment. However, the cover sheet was formed to produce a varying standoff distance in the concave area to adjust the collision angle. After the base section was reinforced with concrete, the parts were assembled as shown in Figure 9. The cover sheet was positioned to produce a standoff distance that varied from 1/8 inch (0.32 cm) at the beginning to 1/4 inch (0.64 cm) at the end of the concave area. Welding was again done with SWP-1 explosive and a loading of 1.65 g/cm^2.

This segment was successfully welded except for the typical short areas at the start and finish of welding. The contour was in close conformance with that of the full-scale nozzle; some deformation occurred at the trailing end of the weld. After visual inspection, the

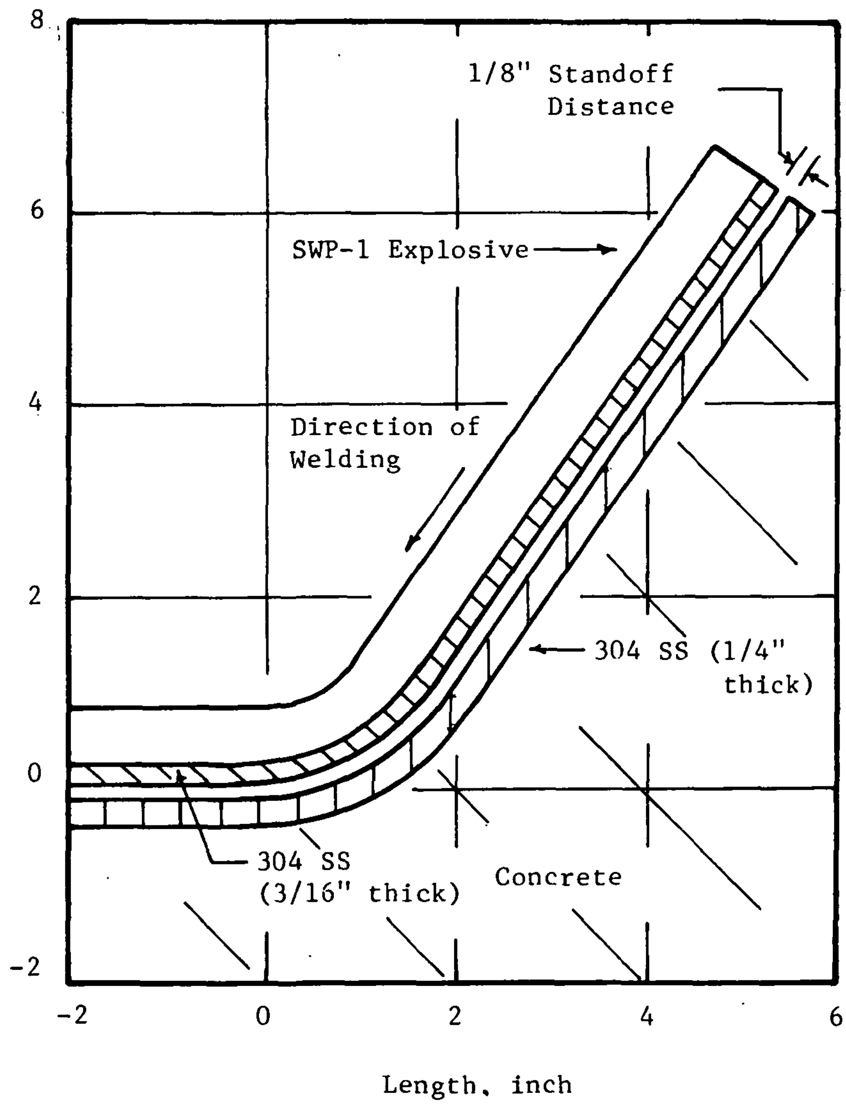


FIGURE 8. EXPLOSIVE WELDING OF UNCHANNELED CONCAVE NOZZLE SEGMENT WITH 1/8 INCH STANDOFF DISTANCE

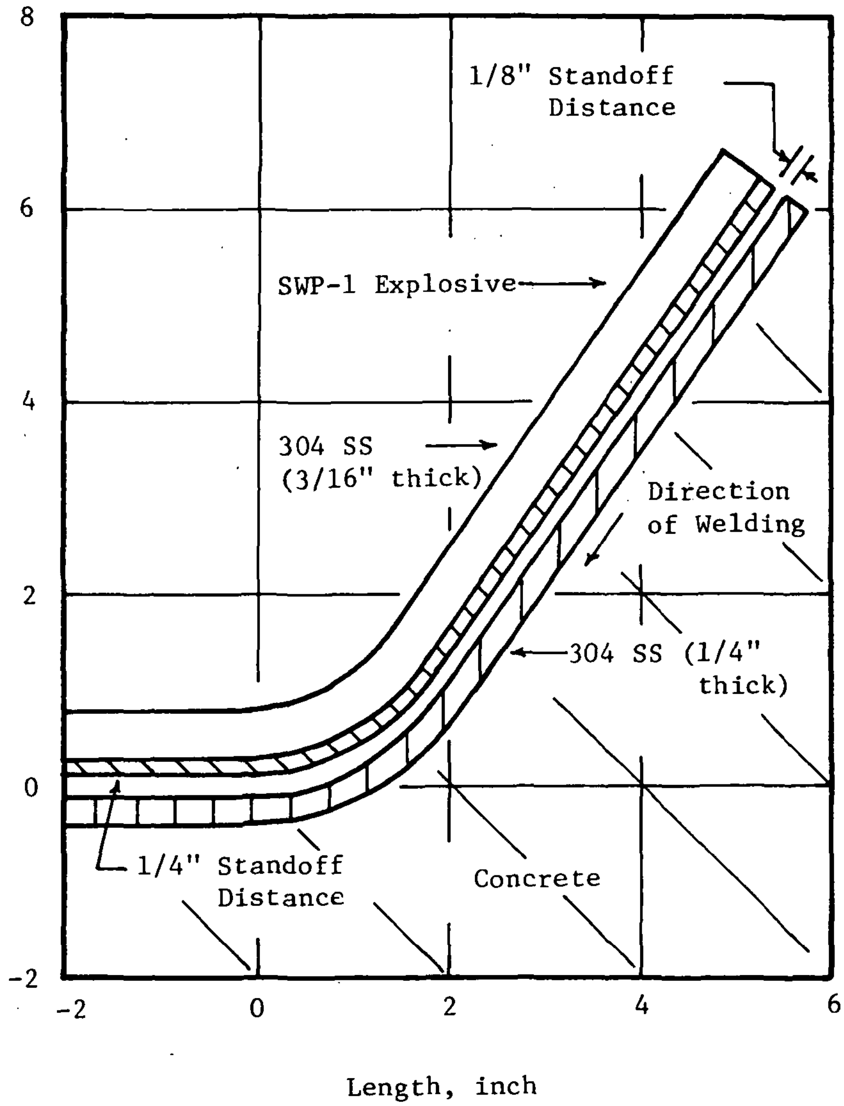


FIGURE 9. EXPLOSIVE WELDING OF UNCHANNELED CONCAVE NOZZLE SEGMENT WITH 1/8 to 1/4 INCH STANDOFF DISTANCE

segment was sectioned to produce samples for metallographic examination. The results of these studies are discussed below.

Section CC-1-1. This section was located at the end where welding was initiated. The wave pattern was somewhat less developed than in previous joints and there was an almost continuous phase along the interface where transient surface melting had occurred (Figure 10a).

Section CC-1-2. This section was located where the concave curvature was most pronounced. As indicated in Figure 10b, the microstructure at the interface varied from a series of melt pockets to an almost solid-state weld; the wave pattern was very small. A large melt pocket is shown in Figure 10c; the cast structure with shrinkage voids is evident.

Section CC-1-3. This section was located near the trailing end of the weld. The joint microstructure resembled that of Section CC-1-2.

The results of this investigation indicated that welding of sections with concave curvatures could be successfully welded; however, the standoff distance between joint members was critical and would have to be carefully controlled.

Convex-Concave Welding

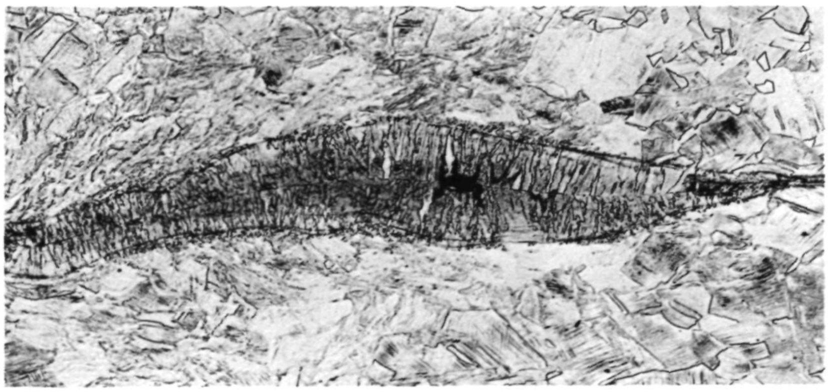
The final series of experiments in the unchanneled studies involved combining the convex and concave regions into a single component to investigate the welding of nozzle sections that would include these two regions and their connecting regions. The section which is located at the inlet end of the nozzle would become the trailing or termination end of the weld in the welding of the actual nozzle. These experiments are described below.

100X 10% Chromic Electro-Etch 1H868

a. Section CC-1-A (located near initiation end)

100X 10% Chromic Electro-Etch 1H869

b. Section CC-1-B (located in concave curvature)



100X 10% Chromic Electro-Etch 1H870

c. Section CC-1-B (located in concave curvature)

FIGURE 10. JOINT MICROSTRUCTURES IN CONCAVE SEGMENT

($1.66\ gm/cm^2$ SWP-1 explosive; 0.32 to 0.64 cm standoff distance)

Segment CCV-1. This segment consisted of (1) a 3/16-inch-thick (0.48 cm thick) 304 SS cover sheet, and (2) a 1/4-inch-thick (0.64 cm thick) 304 SS base section. Both members were about 12 inches (30.5 cm) wide and 15 inches (38.1 cm) long. The cover sheet and base section were formed in a press brake to reproduce the concave-convex curvature of the full-scale nozzle. After the base section was backed up with concrete, the parts were assembled as shown in Figure 11. From the results obtained during the welding of individual convex and concave segments, it appeared that a constant standoff distance of 1/8 inch (0.32 cm) should be maintained from the detonation end through the convex area. Then, the standoff distance should be allowed to increase gradually from 1/8 to 1/4 inch (0.32 to 0.64 cm) through the concave area to the trailing end of the weld. However, the desired standoff distances were not totally achieved with this segment because precise tolerances in forming the cover sheet and base section were difficult to maintain. A constant standoff distance of 1/8 inch from the detonation and through the convex area was readily achieved, but the standoff distance increased from 1/8 inch to 5/16 inch through the concave area and then decreased to 1/4 inch at the trailing end of the weld.

The concave-convex segment (CCV-1) was welded with SWP-1 explosive at a loading of 1.65 g/cm^2. An area 5 inches (12.7 cm) long over the convex curvature was tamped with 0.0625-inch-thick (0.16 cm) lead sheet to investigate the effect of a lower tamping thickness.

The welding of this concave-convex segment was almost completely successful. The contour of the welded segment was generally in conformance with that of the full-scale nozzle except for an area where welding was initiated. Deformation in this area was also observed when the convex segment was welded. Visual examination of sections from this weldment indicated that there were relatively short unbonded areas at the start and finish of welding; unbonds in these areas were expected. However, an unbonded area in the concave curvature (about 1 inch or 2.54 cm long) was of far more concern. The unbond in this area was apparently the

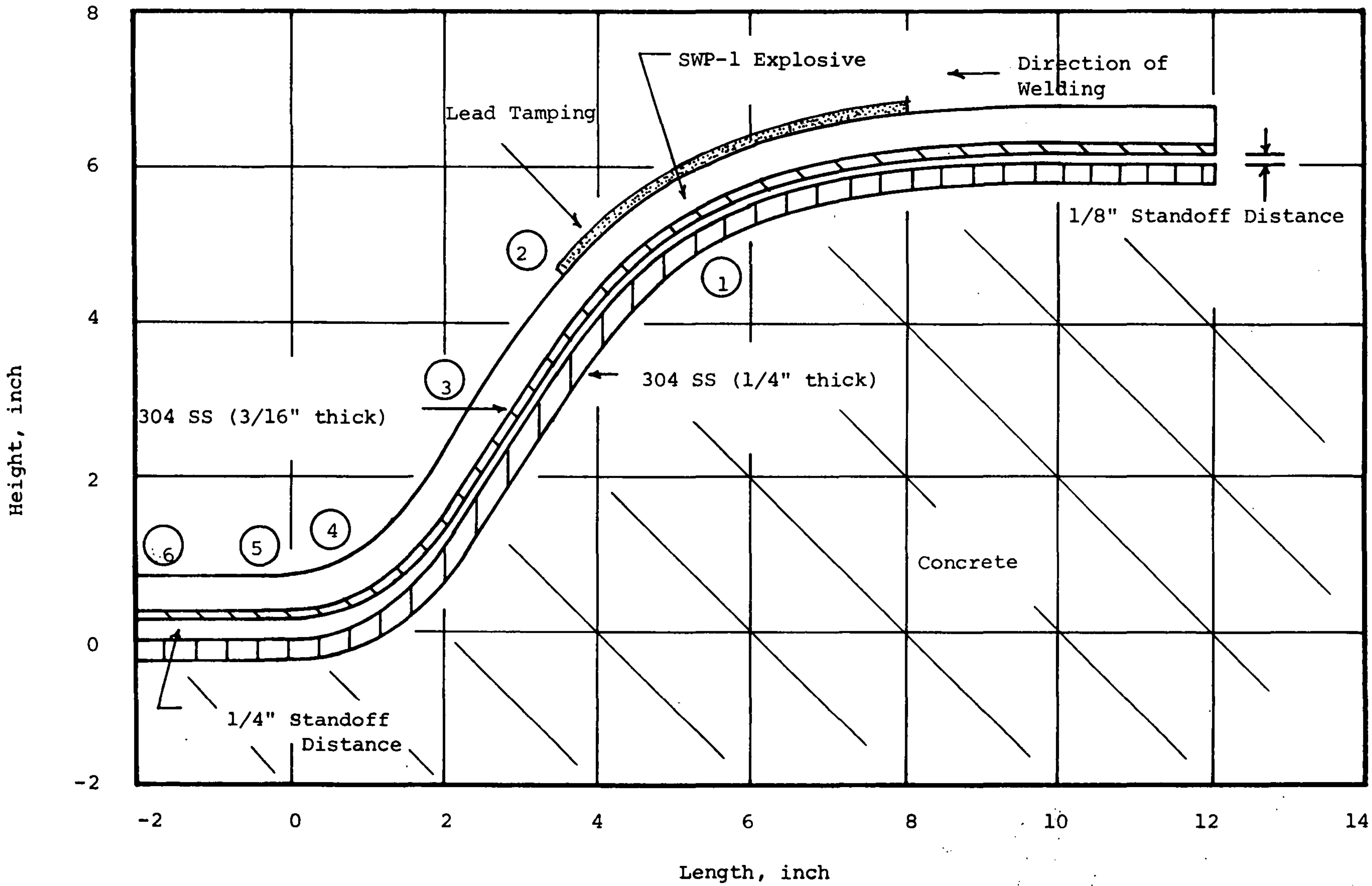


FIGURE 11. EXPLOSIVE WELDING OF UNCHANNELED NOZZLE SEGMENT

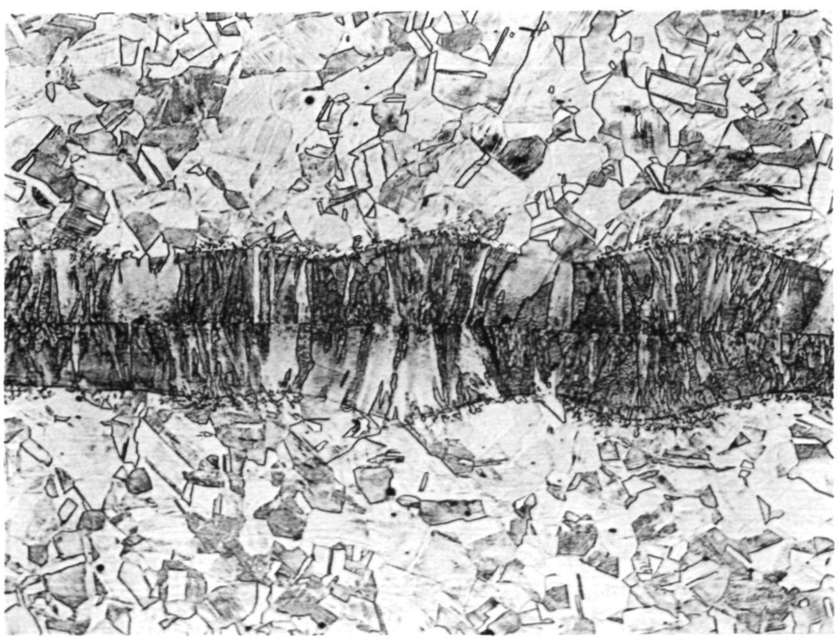
result of improper standoff distances between the cover sheet and the base section. It was similar to the unbond that occurred during the welding of the first concave segment (CC-0) with a uniform standoff distance. In that instance, the unbond was eliminated by adjusting the standoff distance.

Several sections from the welded joint were examined metallographically (the location of these sections is denoted by the circled numbers along the contour of the assembly shown in Figure 11). As can be observed in the attached photomicrographs (Figures 12a-12f), the microstructures vary considerably along the joint interface. These variations are associated with changes in the collision angle (and other related welding variables) as the explosive wave front advances along the contoured interface. The following should be noted:

- The wave pattern along the joint interface varied significantly, depending on the location of the metallographic section. In some instances, the joint interface was almost flat; in others, the wave pattern was well developed.
- The degree of melting at the interface varied widely also as the result of variations in the collision conditions. Gross melting occurred toward the end of the convex curvature and toward the end of the concave curvature where the collision conditions were improper.
- A section of the unbonded area at the trailing end of the concave curvature is shown in Figure 12e. Although this area was once welded, separation occurred due to excessive melting caused by improper collision conditions combined with the residual tensile stresses in this region.

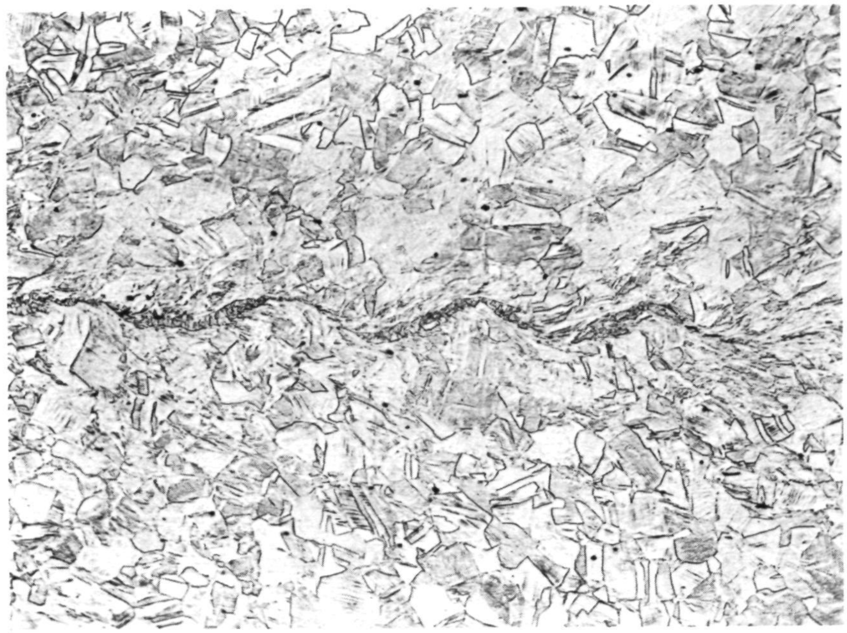
Segment CCV-2. The cover sheet and base section for this segment were prepared in the same manner as those for Segment CCV-1. However, particular care was observed during the forming operation to shape the cover sheet so that the following standoff distances could be

100X a. Location 1 3H025

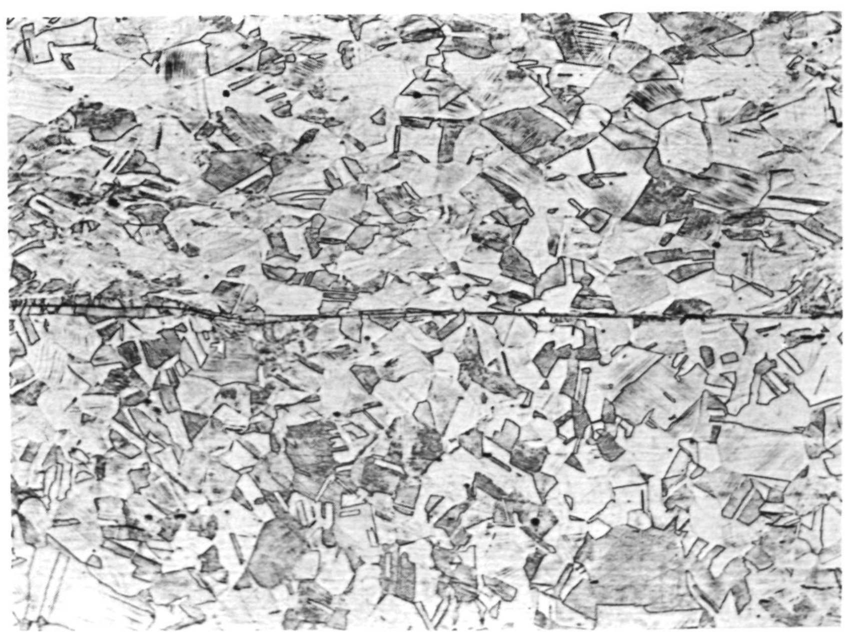


100X b. Location 2 3H026

FIGURE 12. PHOTOMICROGRAPHS OF VARIOUS AREAS ALONG JOINT INTERFACE IN EXPLOSIVE WELDED ASSEMBLY CCV-1

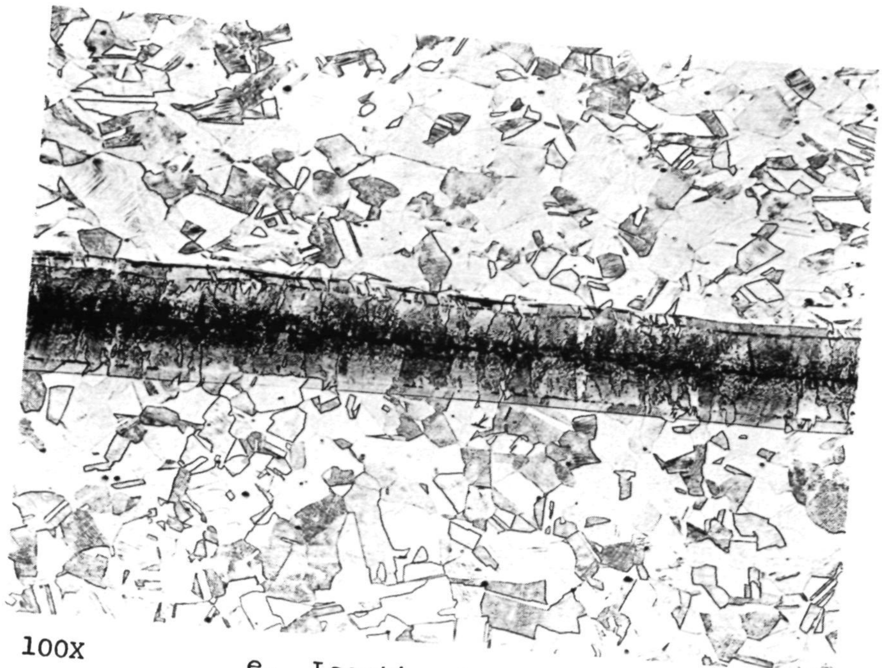


100X c. Location 3 3H027



100X d. Location 4 3H028

FIGURE 12. (Continued)



100X e. Location 5 3H029

100X f. Location 6 3H030

FIGURE 12. (Continued)

maintained: (1) a constant standoff distance of 1/8 inch (0.32 cm) from the initiation end through the convex curvature, and (2) a gradually increasing standoff distance of 1/8 to 1/4 inch (0.32 to 0.64 cm) through the concave curvature to the termination end. The individual parts were assembled for welding as shown in Figure 11. Welding was done with SWP-1 explosive at a loading of 1.65 g/cm^2.

Segment CCV-2 was welded successfully. Visual examination of sections from this segment indicated the expected presence of short unbonded areas at the start and finish of welding. However, complete bonding through the convex and concave curvatures was evident, indicating that a well-controlled standoff distance is essential. Sections from this segment were checked with a dye penetrant. The joint was defect-free except for a very small indication of a void in the concave area.

Discussion of Results

The results of these studies demonstrated that components having combined convex and concave curvatures could be completely and successfully clad by explosive welding. It is essential, however, that the standoff distance between the two components or joint members be carefully controlled in order to achieve uniform collision conditions and complete welding over the entire surface area. The two most critical areas of welding were found to be the end areas of both the convex and concave regions.

Welding of Curved-Channeled Assemblies

Studies were then directed toward combining and adjusting, if necessary, the previously developed parameters and procedures to explosively weld curved-channeled sections with contours essentially identical to those of the full-scale nozzle block. These studies, which were to be the last step prior to welding the actual nozzle, were essential to determine the effect of the presence of channel tooling on the ability to fabricate high-quality, curved weldments. The data accumulated during the welding of unchanneled, curved sections were used as a guide;

however, it was expected that welding would be more difficult over a channeled surface and adjustments in the welding procedures would have to be made as work progressed in these studies.

The following sequence of procedures was used to prepare the parts for the curved-channeled welding experiments.

- Cut flat cover and base sections to overall size.
- Machine channels in base section.
- Fill channels with lead strips to prevent deformation of the ribs during forming to the contoured configuration.
- Form cover sheet and base section to the nozzle contour.
- Remove lead strips from channels.
- Install (cast) Bi-42 Sn support tooling in channels.
- Smooth channel tooling flush with rib or land surface; then undercut tooling 0.005 inch (0.01 cm) below rib or land surface.
- Mask ribs with electroplating stop-off.
- Electroplate 0.005 inch (0.01 cm) nickel over support tooling to isolate and protect this material during the welding operation.
- Remove masking material from rib surfaces to expose them for the welding.
- Cast base section into concrete for support during welding.
- Complete assembly of cover sheet and explosive for welding.

Concave-Convex Segment Welding

Segment CCV-3 (Thick Cover Sheet). This segment consisted of a 304 SS cover sheet, 3/16 inch thick (0.48 cm thick) and a 304 SS base section, 3/8 inch thick (0.95 cm thick).* The overall size of the segment was 11 by 18 inches (27.9 by 45.7 cm). Six channels were machined in the center area of the base section. The channels were 3/16 inch (0.48 cm)

* The base section thickness was limited to 3/8 inch because this was the maximum thickness of stainless steel that could be accurately formed without machining after forming.

wide and 1/8 inch (0.32 cm) deep; the ribs were 1/16 inch (0.16 cm) thick. After the base section was machined, it and the cover sheet were formed in a press brake to the contour of the full-scale nozzle. The channel tooling was installed and the base section was prepared for welding in accordance with the procedures listed previously (Figure 13).

After the base section was cast into the concrete support, the components were assembled for welding as previously shown in Figure 11. The standoff distance used between the cover sheet and base section was the same as that which had been used to successfully weld segment CCV-2. During setup, some difficulty was encountered in achieving the accurate standoff distance required in both the convex and concave area because the cover sheet was not formed accurately enough. A loading of 1.65 g/cm^2 of SWP-1 explosive was used for welding with 0.0625 inch (0.16 cm) thick lead tamping over the convex surface area of the explosive.

Following welding, the tooling was removed by heating the welded assembly to a temperature slightly above the melting point of the Bi-42 Sn tooling alloy. The molten tooling was then removed by blowing compressed air through the channels. To evaluate the weld, the segment was sectioned parallel to the direction of welding in two areas: (1) the channeled area and (2) the unchanneled areas on either side. The welds in these areas were then inspected visually and with the aid of a dye penetrant. The following were observed:

- Unchanneled Areas. The cover sheet was well bonded to the base section except in the concave area at the nozzle inlet; this result was not unexpected because the standoff distance in this region was not as accurate as desired prior to welding.
- Channeled Area. The cover sheet appeared to be welded to the ribs only in areas where the contour was straight or slightly curved. Unbond was observed where the curvature was pronounced; i.e., in the convex and concave regions. Microscopic examination of the faying or welding surfaces of the cover sheet and ribs revealed the presence of the Bi-42 Sn tooling on these surfaces. While coating of these surfaces with the tooling material probably occurred during the tooling - removal operation, it obscured any detail which would have indicated the

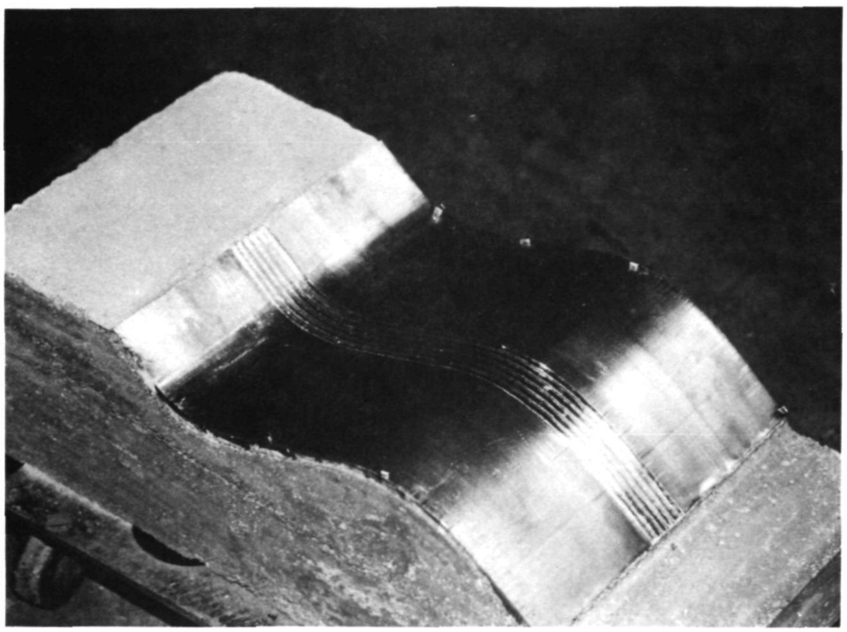


FIGURE 13. BASE SECTION OF SEGMENT CCV-3

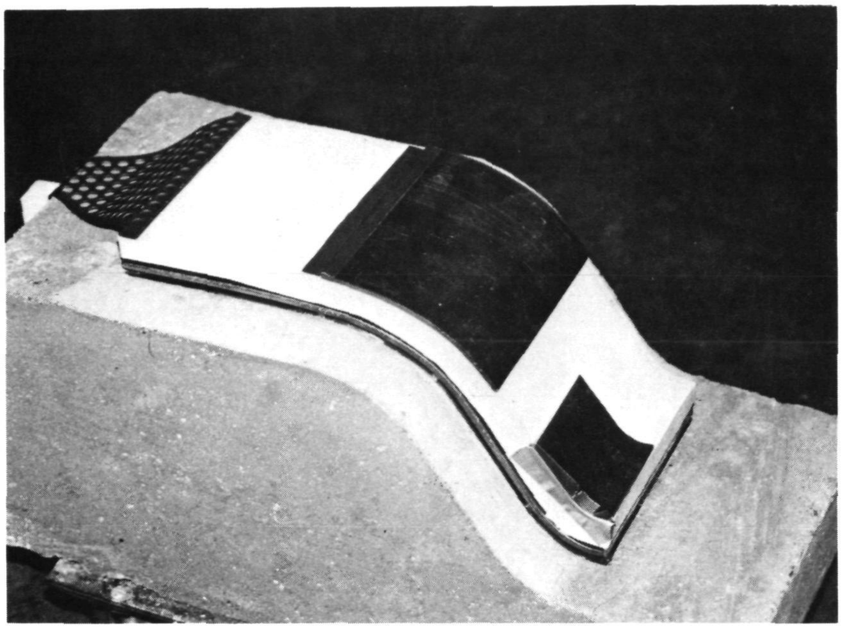
cause of nonwelding or weld failure in these regions.

Segment CCV-4 (Thick Cover Sheet). Since the difficulties in welding appeared to be largely associated with the inability to obtain the desired standoff distances between the cover sheet and the base section, the parts for a second curved, channel segment were prepared. The cover sheet and base section thicknesses were the same as those used in Segment CCV-3; their overall dimensions were the same also. Six channels were machined in the center area of the base section. Particular care was observed in forming the cover sheet and base section in order to obtain the desired standoff distances in areas where the curvature was most pronounced.

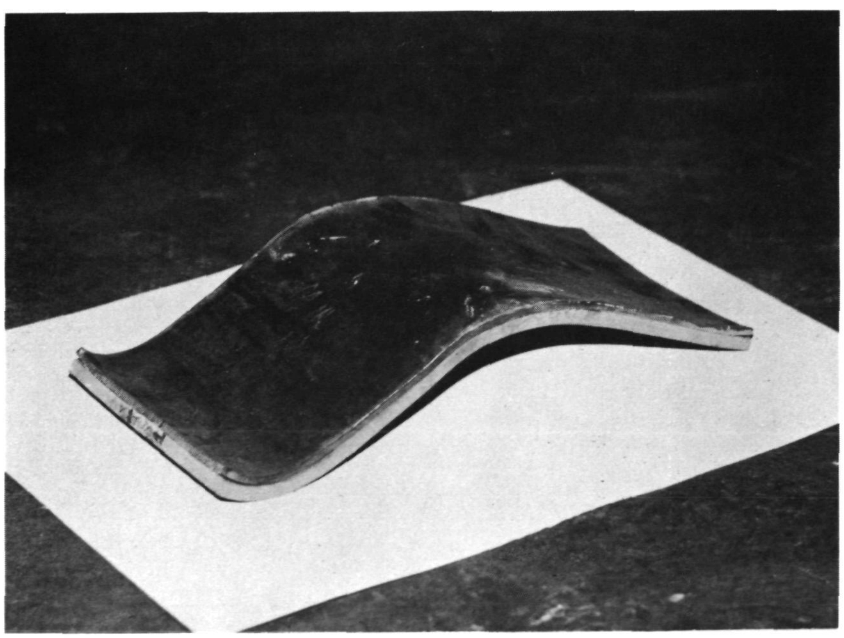
The parts of this segment were prepared for welding in accordance with previously outlined procedures and they were assembled with the standoff distances indicated in Figure 11. Part fitup was much better than that obtained with Segment CCV-3. Welding was done with SWP-1 explosive at a loading of 1.65 g/cm^2; again, 0.0625 inch (0.16 cm) thick lead tamping was placed over the convex area. This segment is shown before and after welding in Figures 14a and 14b.

The tooling was not removed from this segment after welding in order to preserve all details in case unbonds in the channeled portion of the segment were noted. Again, the segment was sectioned parallel to the direction of welding to produce specimens from (1) the channeled area with the support tooling in place, and (2) the unchanneled areas. These specimens were evaluated with the following results:

- Unchanneled Areas. The cover sheet was generally well bonded to the base section. Some lack of bond was observed in regions where the segment curvature was most pronounced, particularly toward the trailing ends of each region.
- Channeled Areas. The cover sheet was welded to the ribs only in areas where the segment contour was flat or slightly curved; welding did not occur in the convex or concave areas or in the region joining them. While



a. Before welding



b. After welding

FIGURE 14. EXPLOSIVE WELDING OF PARTIALLY CHANNELED SEGMENT CCV-4

better control of the standoff distance improved welding in areas where channels were not present, it did not eliminate problems with welding in the channeled area. To study the nonwelded areas further, the channeled portion of the segment was sectioned several times in the area where the curvature was most pronounced; these sections were examined visually and microscopically. In most instances, the cover sheet was separated from the base section by chiseling to expose the tooling and rib surfaces. In the regions of most severe curvature (and particularly toward the trailing ends of these regions), the tooling was heavily worked and there was evidence of surface melting. These findings indicated inproper and possibly excessive collision conditions in these regions.

However, the most important observation was that welding had originally occurred over the entire length of the specimen. This was evidenced by (1) the presence of a wave pattern on the rib surfaces and on corresponding areas of the cover sheet, and (2) the welding of the nickel plating that covered the tooling to the cover sheet. While welding had indeed occurred, the resulting rib-to-cover sheet joints were fractured immediately after welding by reflected shock waves or stresses associated with the explosive welding process.

This welding experiment produced some very revealing results and some significant conclusions:

- Welding in channeled areas produced different results than it did in unchanneled areas. These differences resulted primarily from the presence of the support tooling required for this particular nozzle configuration.

The acoustic impedance (the product of the material density and its sound velocity) of the Bi-42 Sn tooling material is significantly different from that of the nickel cover sheet on the stainless steel base section. The acoustic impedance mismatch results in the generation of unfavorable reflected tensile shock waves at the cover sheet-tooling interface immediately after welding.

- The strength of the narrow rib-to-cover sheet joints was not great enough to withstand the reflected tensile stresses generated as the result of the acoustic impedance mismatch of the channel support tooling.
- The cover sheet thickness appeared to play an important role in the welding of curved, channeled segment welding. During welding, the ratio of cover sheet thickness to radius of curcature is important in achieving uniform collision conditions. The greatest problems occur when this ratio is large; i.e., when a thick cover sheet is welded to a section with a severe curvature. Also, the use of a thick cover sheet produces a greater kinetic energy release and a longer lasting pressure pulse at the collision (or welding) interface. As a result, the chances of melting the Bi-42 Sn support tooling are increased and the duration of the reflected tensile stresses acting on the rib-to-cover sheet joints are increased as well. The severity of these problems would be minimized by reducing the cover sheet thickness.

Segment CCV-5 (Thin Cover Sheet). Based on the results of the preceeding experiment, Segment CCV-5 was prepared with several changes in its design as indicated below:

- As in the case of the full-scale nozzle, the entire surface of the base section was channeled.
- The base section was made from 405 SS and the cover sheet was made from nickel, the same materials used in the full-scale nozzle.

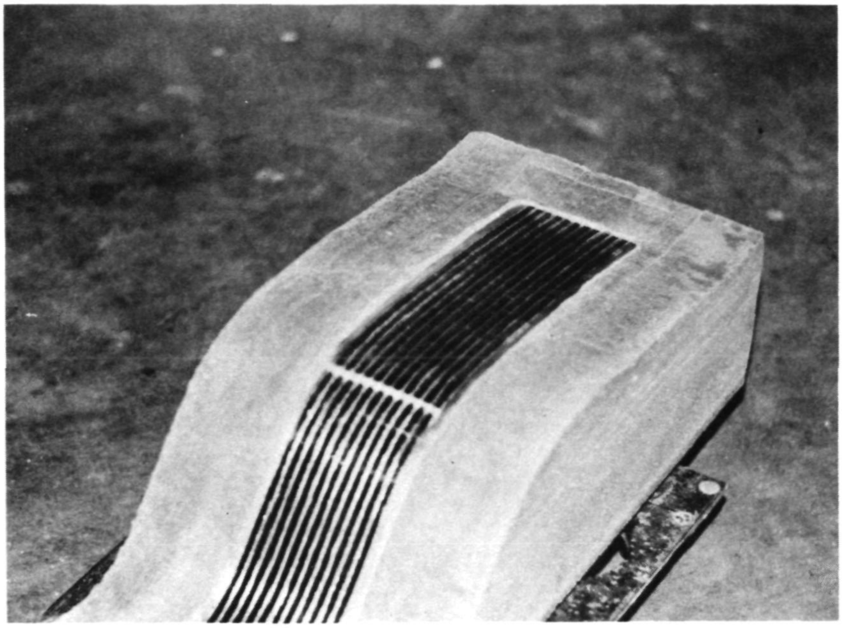
- The cover sheet thickness was 0.040 inch (0.10 cm) instead of 3/16 inch (0.48 cm).

Of these changes, the reduction of the cover sheet thickness was most significant. As discussed above, this change was made to reduce (1) the magnitude of the cover sheet kinetic energy and (2) the duration of the shock wave and its reflections during welding.

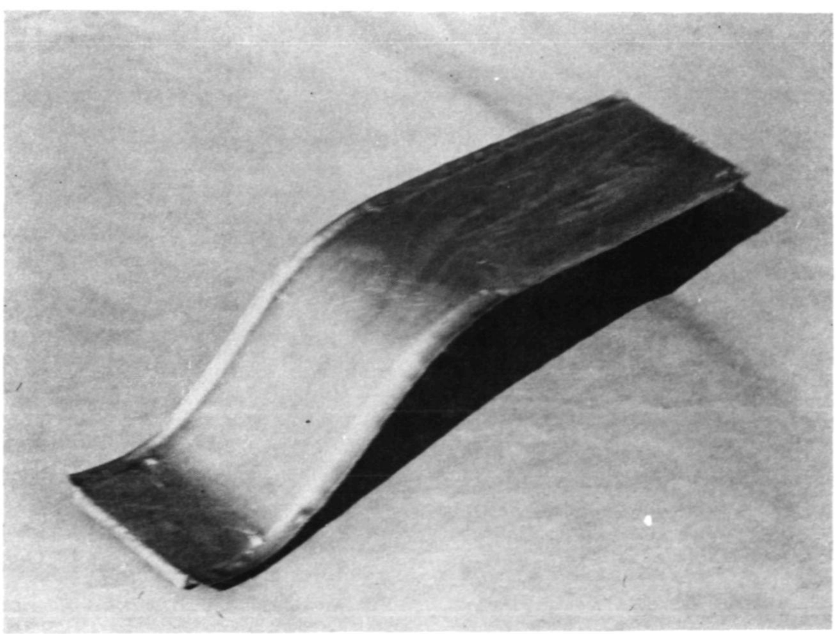
Before Segment CCV-5 was prepared and welded, test specimens consisting of a 0.040 inch (0.10 cm) thick nickel cover sheet and a 3/8 (0.95 cm) thick 405 SS base section were welded to determine the welding parameters; specimens were welded with standoff distances of 0.060 and 0.080 inch (0.15 and 0.20 cm). Welding was done with SWP-1 explosive at a loading of 1.32 g/cm^2. Acceptable joints were produced with either standoff distance. Based on these results, 0.080 inch was selected as the basic standoff distance for welding Segment CCV-5, because larger standoff distances are more tolerant of inconsistencies in the fitup between the cover sheet and the base section than smaller ones.

Segment CCV-5 consisted of a 0.040 inch (0.10 cm) thick nickel cover sheet and a 3/8 inch (0.95 cm) thick 405 SS cover sheet. The base section was 4 inches (10.2 cm) wide and the cover sheet was 6 inches (15.2 cm) wide; both members were 24 inches (61.0 cm) long. Channels were machined across the entire width of the base section. The channels were 1/4 inch (0.64 cm) wide and 0.10 inch (0.25 cm) deep. The cover sheet and base section were formed to the contours of the full-scale nozzle. Then, the tooling was installed in the base section and this part was prepared for welding in accordance with previously described procedures.

The parts were arranged for welding as shown in Figure 11 with (1) a constant standoff distance of 0.080 inch from the start of welding through the convex area, and (2) a standoff distance varying from 0.080 to 0.100 through the concave area to the finish of welding. Lead tamping (1/16 inch thick) was placed over the entire convex area and over half of the concave area. Welding was done with SWP-1 explosive at a loading of 1.32 g/cm^2 (Figure 15a).



a. Segment prepared for welding



b. Welded segment

FIGURE 15. EXPLOSIVE WELDING OF FULLY CHANNELED SEGMENT CCV-5

Visually, the segment appeared to be well bonded except for a bulge in the cover sheet that occurred well into the convex area (Figure 15b). The existence of a large void in this location was confirmed by the examination of longitudinal sections from this segment. Also, minor bulging of the cover sheet in areas over the tooling between the rib-to-cover sheet welds was observed. These bulges indicated that some reflected tensile stresses were still present. While they were of sufficient magnitude to bulge the cover sheet in areas over the tooling, they were generally not strong enough to fracture the rib-to-cover sheet welds.

During the examination of sectioned specimens from this segment, some voids and unbonds were observed in the concave area. The removal of the cover sheet from this region and from the heavily bulged region over the convex curvature revealed, as before, that welding had occurred with subsequent fracturing of the joints. Also, evidence of surface melting and damage to the tooling indicated that the collision conditions in these regions were not optimum and might have contributed to fracturing of the welded joints.

In general, the results of this experiment (Segment CCV-5) showed that welding was much improved when the thickness of the cover sheet was reduced. While some unbonded areas were observed where the segment curvature was most pronounced, they were much less extensive than those produced when a thick cover sheet was welded to the base section.

Discussion of Results

The explosive welding of channeled, curved segments has revealed the presence of a problem whose existence was not indicated during the welding of unchanneled segments with similar curvatures. When unchanneled members were welded together, joint strength was based on the entire surface of the weldment. In contrast, when a cover sheet was welded to a channeled base section, the total joint strength was based on the strengths of individual rib-to-cover sheet joints: these joints were only 1/16 inch wide. Apparently, the joint between the unchanneled members was strong enough to withstand the reflected stresses produced by the explosive welding operation, but the rib-to-cover sheet joints were not. Among the easiest ways to decrease these forces is to reduce the cover sheet thickness. The results confirmed the validity of this approach, but sufficient work was not done to finalize the parameters and resolve all of the technical details.

Preparation of Full-Scale Nozzle

The full-scale nozzle base section was prepared for welding in general accordance with the procedures developed to prepare small channeled structures for cover sheet-to-base section welding. However, some procedural changes were required because of the size of the nozzle base section. The important aspects of this work are discussed below.

- Manifold Preparation. The front and rear manifold cavities were filled with Bi-42Sn tooling to provide support to the areas immediately above them. To seal the cavities, rubber stoppers were placed in the ports and were cemented in place with an epoxy resin structural adhesive. Then, the molten tooling material was poured into the cavities to fill them completely.
- Channel Tooling Installation. For ease in handling, the tooling material was cast into bars. Before filling the channels, the entire nozzle structure was heated to within 5 F of the melting point of the tooling material. Then, the tooling was installed in the channels with the aid of a small oxyacetylene torch; an acid flux was used to promote wetting of the channel surfaces by the molten tooling. Because of its narrow melting range and fluidity, it was necessary to install the tooling in one small area at a time. To prevent runoff of the tooling, these areas were positioned horizontally by raising or lowering one end of the nozzle structure with a hoist. After the channels were completely filled, it was necessary to remelt and reflux some areas repeatedly to eliminate voids, lack

of wetting, and other defects.

- Surface Preparation. After the channel tooling was installed, the surface of the nozzle structure was finished with an orbital sander; coarse paper was used to remove excessive deposits of tooling and expose the ribs. Fine paper was then used for final surfacing.
- Undercutting. To prepare the tooling for electroplating, it was undercut 0.005 inch (0.01 cm). Several methods of undercutting were evaluated. This operation was best performed with a suitably shaped chisel or knife blade.

The nozzle structure is ready for electroplating and final surfacing. However, the electroplating operation has been deferred until the problems associated with the explosive welding of channeled, curved segments are resolved.

CONCLUSIONS AND RECOMMENDATIONS

This research and development program was conducted to demonstrate the feasibility of fabricating large channeled nozzle structures for wind tunnel applications by explosive welding. In the course of this investigation, work in several important areas was undertaken as follows:

- Studies were first conducted to select the support tooling required to maintain the dimensional integrity of the channeling in the nozzle during the explosive welding operation. The number of potential tooling systems to be considered and evaluated was limited because of the complex geometry of the channels, the susceptibility of the nickel cover sheet to acid attack, and the need for quick and complete removal of the tooling after welding. It was determined that a Bi-42Sn alloy covered on the exposed surface with electroplated nickel, 0.005 inch (0.01 cm) thick, met the requirements for a support tooling system. This decision was based on the successful conclusion of a series of explosive welding experiments in which a 0.250-inch (0.63 cm) thick cover sheet was welded to a 1-inch (2.5 cm) thick flat channeled base section. Although the installation of the support tooling in the channels was not difficult, it was time consuming. To provide the required support, particular care was needed to insure that the tooling was free of voids and completely filled the channels.

- Secondly, studies were conducted to develop the explosive welding parameters and procedures required to obtain a complete, uniform weld over the entire length of the nozzle surface. As expected, the most critical area was the full reverse curvature at the inlet end of the nozzle. These studies indicated that such a weld could be successfully made in a relatively large, unchanneled structure consisting of a 0.187-inch (0.48 cm) thick nickel cover sheet and a 0.375-inch (0.95 cm) thick 405 SS base section which was formed to the contour of the nozzle block. The most critical parameter in achieving sound welds was the preciseness of the standoff distance between the cover sheet and base section (particularly in areas where the curvature was most severe).
- The third and final area investigated was the welding of contoured cover sheet-to-base section assemblies with channelling, the contours of which essentially duplicated those of the full-scale nozzle. These studies demonstrated the sensitivity of the explosive welding process to the combined effects of the support tooling and the complex curvature of the joint members. An evaluation of the results indicated that the problems encountered during this work were not so much in obtaining a good weld between the cover sheet and the rib or land surface of the base section, but in maintaining

weld integrity immediately after welding. It was determined that problems associated with failure of the weld in the most severely contoured regions were related to the rebound forces produced by reflection of the shock or stress waves generated by the welding collision back through the weld interface. The effects of the reflected stress waves were augmented by the acoustic impedance mismatch between the joint materials and the channel support tooling and by the need for the narrow rib-to-cover sheet welds to withstand the total loading produced by these waves. Limited studies in which the nickel cover sheet thickness was reduced from 0.187 inch (0.48 cm) to 0.040 inch (0.1 cm) indicated that welding was significantly improved. This concept should be pursued further.

In the course of this program, the Bi-42Sn support tooling was cast into the channels and manifolds of the NASA nozzle block and the surface of the block was prepared for electroplating. In view of the problems encountered in welding curved, channeled assemblies, work on final preparation of the nozzle block for welding was deferred until these problems were resolved and success in welding was assured.

Prior to welding the full-scale nozzle structure, it is recommended that additional studies be conducted to resolve the problems associated with the fabrication of contoured assemblies with complex channeling. Based on the analysis of the results and conclusions of this program to date, these studies should be directed toward investigating the following specific areas that, individually or combined, offer strong potential for solving these problems and successfully completing the fabrication of the nozzle assembly.

- Based on the encouraging results of limited experiments with the thin (0.04 inch) nickel cover sheet, additional studies with cover sheet material of similar thicknesses should be conducted to further prove the merit of this approach. The reduction of cover sheet thickness is important because the mass of the cover sheet is decreased and the magnitude of the rebound forces acting in the narrow cover sheet-to-rib welds is reduced as a result. Since the thinnest section of the cover sheet in the actual nozzle is slightly less than 0.040 inch, the entire nozzle surface could be clad with a 0.040 to 0.050-inch-thick nickel sheet. After the nozzle surface is clad, the reinforced or thicker areas at the inlet and outlet ends of the nozzle could be produced by explosively welding additional sheets of the required thickness to the nickel cover sheet. Alternatively, these areas could be built up by electroplating.

- Because of limitations on the thickness of the channeled base sections that could be accurately formed, the base sections used in current experimental studies were considerably thinner than will be encountered in the actual nozzle structure. The difference in base section thickness could be significant from the viewpoint of the time required for the shock wave to travel through the base section and be reflected back to the weld interface and the amount the shock wave will decay or decrease in magnitude before it returns to the weld interface. During the current program, there was eivdence of the significance of base section thickness in experiments conducted with flat, channeled base sections with a thickness of one inch. In these experiments, there was no post-welding fracturing of the cover sheet-to-rib welds. To avoid obtaining data that are not representative of conditions to be encountered during the fabrication of the full-scale nozzle, the channeled base section of the experimental assemblies should be approximately as thick as the channeled area of the nozzle. While working with sections from a full-scale nozzle represents the ideal case, such sections are not likely to be available. Thus, relatively thick channeled base sections should be produced for experimental studies. Sections at least 1 inch thick are recommended.

- An analysis of the program results also suggests that attention should be directed toward explosive characteristics in future studies. An explosive with a lower detonation velocity than SWP-1 (that is, lower than 3000 m/sec) could potentially improve welding quality significantly and, at the same time, reduce the magnitude of the rebound forces acting on the welded joints. These benefits would result from a lower cover sheet velocity and a lower collision point velocity which would be effective in reducing the magnitude of the shock wave and would be more compatible with the sonic velocity of the channel support tooling.

Initially, experiments designed to study each of the suggested areas of research should be undertaken with channeled assemblies incorporating convex and concave curvatures to optimize the procedures required to clad the base section with a thin nickel cover sheet. The data resulting from these studies should then be combined to establish the procedures for welding sections with full-scale reverse curvatures. The results from the current program will be used to guide these studies.

The fabrication of the NASA nozzle structure should be undertaken as soon as the recommended studies are successfully concluded.

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