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ASD TECHNICAL REPORT 61-124

EXPLOSIVE WELDING

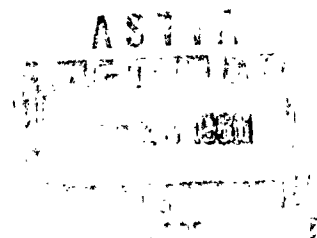
VASIL PHILIPCHUK

AMERICAN POTASH & CHEMICAL CORPORATION
NATIONAL NORTHERN DIVISION

AUGUST 1961

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AERONAUTICAL SYSTEMS DIVISION



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EXPLOSIVE WELDING

VASIL PHILIPCHUK

*AMERICAN POTASH & CHEMICAL CORPORATION
NATIONAL NORTHERN DIVISION*

AUGUST 1961

DIRECTORATE OF MATERIALS & PROCESSES
CONTRACT No. AF 33(616)-6797
PROJECT No. 7351

AERONAUTICAL SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

FOREWORD

This report was prepared by the National Northern Division of the American Potash & Chemical Corporation under U.S.A.F. Contract No. AF 33(616)-6797. This contract was initiated under Project No. 7351, "Metallic Materials", Task No. 73516, "Welding and Brazing of Metals". This work was administered under the direction of the Directorate of Materials and Processes, Deputy for Technology, Aeronautical Systems Division, with Mr. Robert E. Bowman acting as project engineer.

This report covers work conducted from January 1960 through January 1961.

The work described herein, its objectives, and conclusions were possible only through the splendid cooperation and diligent work of the following:

<u>Level</u>	<u>Name</u>	<u>Representing</u>
Project	Mr. Robert Bowman	ASD
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Technical	Mr. Russell Hatch	NND - AP&CC
Machine Work	Mr. Bert Curtis	NND - AP&CC

Acknowledgment to New England Materials Laboratory, Inc., Medford, Massachusetts is made for the metallographic and physical analysis of the test specimens.

ABSTRACT

Methods were developed for the successful welding by the use of explosive forces of 4340 Steel to 4340 Steel, 6 Al-4V Titanium to 6 Al-4V Titanium, and Molybdenum to 310 Stainless Steel. No success was achieved with B120 VCA Titanium to B120 VCA Titanium and Molybdenum to Molybdenum.

Test specimens were in sheet or strip form. All welds were lap-type, with one piece of metal directly over or lapped over the other.

Successful welds of the above three metal combinations indicate that explosive forces can be utilized for lap weldments of sheet metals when the proper test parameters and techniques have been investigated and developed.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:



I. PERLMUTTER
Chief, Physical Metallurgy Branch
Metals and Ceramics Laboratory
Directorate of Materials and Processes

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I. INTRODUCTION

This program was sponsored by the Research Group of the Wright Air Development Division with the objective of determining processes for welding with explosive forces sheet materials that are most difficult to weld conventionally.

Previous work on explosive welding in this country had been confined to the aluminum, plain steels, and nickel alloys. Analyses of National Northern's nickel-to-nickel welds by Wright Field personnel indicated that materials could be welded through the use of explosive forces that are properly applied.

With the future necessarily holding a greater use of the high-temperature or refractory metals, this program of research to determine techniques and processes for the welding of these materials with explosive forces was proposed by National Northern and duly sponsored by the Air Force's research-minded personnel.

The program involved the exploration of the following combinations of metals or alloys:

- a. 4340 Steel to 4340 Steel
- b. B120 VCA Titanium to B120 VCA Titanium
- c. 6 Al-4V Titanium to 6 Al-4V Titanium
- d. Molybdenum to Molybdenum
- e. Molybdenum to 310 Stainless Steel

Limited funds and non-availability of material did not permit exploration into the fields of:

columbium
beryllium combinations

The research work conducted on the combinations listed above, "a" through "e", is the subject of this report. The results reported in four interim progress reports to the Air Force in Dayton are detailed and analyzed in this, the final report.

II. EXPERIMENTAL WORK PROCEDURE

The procedures for welding sheet materials were varied to determine those required and necessary for the successful weldment of each combination under study. A great portion of the preliminary work under this study was conducted on explosive welding of 4340 steel to 4340 steel. Material used was supplied by the Air Materiel Command at Dayton, Ohio, under their large-sheet program, conducted with United States Steel and various sub-contractors, in which National Northern was fortunate to be one of the participants. The use of the 4340 steel

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sheet enabled us to conduct a larger number of preliminary experiments prior to finalizing procedures for weldment of sheet materials.

The variables or parameters that were studied on the 4340 steel to 4340 steel weldments were as follows:

- a. Etchants or surface treatment
- b. Spacing between sheets
- c. Explosive forces applied
- d. Initiating directions
- e. Medium transmitting the forces

The above parameters were varied to determine the areas or regions required for welding of the material.

A. Etchants or surface treatment was varied as follows:

- (1) None (surface as received)
- (2) Clean (surface degreased)
- (3) Rough (surface degreased and roughened with emery cloth)
- (4) Mild etchant, aqua regia - cupric chloride solution for 15 seconds
- (5) Same as (4) except etched for 30 seconds
- (6) " " (4) " " " one minute
- (7) " " (4) " " " two minutes
- (8) " " (4) " " " three minutes

B. Spacing between sheets was varied from none (surface contact) to .020". In addition, angled spacing of up to 10° was used in tests to determine optimum spacing or geometry for welding. Figure 3 shows metal being set up for test.

C. Explosive forces applied were varied by changing explosive type, geometry, quantity, and distance (stand-off) from the sheet material to be welded. Figure 1 shows a set-up for test. The explosives used in test were Trona 506 and 509 which have detonation rates of 7800 and 7500 m/s respectively. Stand-off distances, or distance from the sheet, were 1/2", 1", 1½", and 2". Explosive weights or quantity were 50, 100, 150, and 200 grams. The varied combinations would produce a pressure range of 10,000 to 400,000 pounds-per-square-inch. Figure 4 shows preparation of the explosive for welding.

D. Initiating directions were varied by utilizing an end and a top initiation. The end initiation is shown in Figure 2, while the top initiation is shown in Figure 1. By going to an end initiation, the action of compression of the gases (air) between the sheet material is changed to an orifice-type of compression-escape. This type of compression required so much larger quantities of explosive to produce pressures equal to those obtained from the top initiation that fracturing of the material would occur.

E. Medium transmitting the forces was primarily water, although it was found upon testing with other materials that the chemical reactions in the explosive have not been completed upon initial pressure contact of the sheet to sheet. The gaseous products moved the water medium away and brought the gases (during the chemical reaction in the explosion) in contact with the material to be welded. This resulted in burning and distortion of the sheets. The next move was to use a buffer or medium other than water that would not move and yet protect the sheet

during pressure application. The types experimented with were rubber, other metals in sheet form, chipboard, and plastics. The chipboard was selected as being the most applicable medium for welding, since it can be controlled and varied more readily than the other materials.

Tests conducted did point up the fact that controlled conditions are required for welding with explosive forces. Although some combinations can be varied with success, the general conditions must be established for each type of material. The material itself can vary the conditions by its physical properties and geometry (thickness) being changed.

III. WELDING OF 4340 STEEL TO 4340 STEEL

A. Material: Most tests of welding the 4340 steel to itself were conducted with 3" x 3" sections. Tensile test specimens were long strips 1/2" or 1" wide with a 1/2" or 1" wide overlap. Some tests were conducted on 12" long x 2" wide strips. All of the 4340 steel in this test was .030" thick and was obtained from the Air Materiel Command's supply of large sheet that was manufactured by United States Steel. Since no analysis or physicals were received by National Northern from either AMC or USS, typical analysis and physicals of annealed 4340 steel follow:

<u>C</u>	<u>Mn</u>	<u>P</u>	<u>S</u>	<u>Si</u>	<u>Ni</u>	<u>Cr</u>	<u>Fe</u>
.40	.70	.04	.04	.30	1.90	.80	Bal.

<u>T.S.(psi)</u>	<u>Y.P.(psi)</u>	<u>% Elong.</u>	<u>Hardness</u>
101,000	69,000	21.0	207 BHN

B. Test Conditions: After many tests utilizing the variables outlined under EXPERIMENTAL WORK PROCEDURE, the following test conditions were found to be the best for welding of the 4340 steel to 4340 steel:

Explosive:	TRONA 509, aluminized RDX-TNT composition
Explosive Geometry:	2" diameter x 5/8" high
Explosive Weight:	98 grams, top initiation (for 3" x 3" pcs.) 35 grams, top initiation (for 1" x 3" pcs.)
Etchant:	Aqua regia-cupric chloride solution on surfaces to be welded for 2 minutes
Medium and Stand-Off:	Chipboard, 1.0" thick between explosive and metal. Water surrounded the sides and top of explosive charge
Clearance between Metal Sheets:	Metal sheet placed on top of another metal sheet. Clearance between sheets averaged .005"
Set-up:	See Figures 1, 3, and 4

C. Test Results: Metallurgical analysis of the welds of 4340 steel to 4340 steel was as follows:

Metallographic Examination: This examination confirmed the visual examination that the periphery of the lapped surface was welded with the central portion being just in intimate contact. Photomicrographs of the material and the welded interface are shown in Figures 5 and 6. The thin white layer of varying thickness, up to .002" (Figure 6), is the weld interface and appears martensitic in structure.

Bend Tests: The 3" x 3" specimens when bent 180° flat showed no evidence of separation.

Hardness: A microhardness survey of a section through the welded area indicated the interface or welded area to be very hard. The hardnesses follow:

<u>Location</u>	<u>Hardness, VPN</u>	<u>Converted Rockwell "C" Hardness</u>
Near one side	245	23
.005"	228	21
.010"	254	25
.015"	245	23
.020"	274	28
.025"	306	32
White interface	824	62
.035"	297	31
.040"	285	30
Near other side	254	25

This confirms previous findings in other materials that the welded interface of explosive welds is harder than the parent material and, hence, more brittle.

Tensile Shear Tests: Tensile shear tests were conducted on strips 1/2" wide with 1/2" overlap and 1" wide with 1" overlap and 4" long. The specimens all broke in the region adjoining the overlap and never at the welded joints. This indicated that the welds were stronger than the parent metal, and that the region adjoining the overlap was weakened during explosive tests (primarily through thinning during welding and not as a heat-affected zone). Visual examination of welded strips has confirmed this fact. The three tensile tests conducted produced the following results:

<u>4340 Specimen</u>	<u>Failure Load (lbs.)</u>	<u>*Ultimate Tensile Strength (psi)</u>
1/2" wide overlap	1190	80,000
1" wide overlap	2180	73,000
1" wide overlap	2660	88,000

*These values are based on a .030"-thick specimen. Since thinning occurred in the regions where the specimens failed, a more accurate tensile strength would be closer to 100,000 psi, the original parent metal strength.

IV. WELDING OF 6 AL-4V TITANIUM TO 6 AL-4V TITANIUM

A. Material: These explosive welding tests were also conducted on 3" x 3" sections and on 1"-wide strips with a 1/2" overlap used for the welding surface. All material in this phase was .020" thick. The titanium was purchased from Crucible Steel Company of America. Its chemical and physical properties follow:

6 Al-4V Titanium (C-120AV Hot-Rolled Annealed)
Crucible Heat No. G5913

<u>H₂</u>	<u>C</u>	<u>N</u>	<u>V</u>	<u>Al</u>	<u>Fe</u>	<u>O₂</u>	<u>Ti</u>
.004	.06	.01	4.0	5.7	.10	.09	Bal.

<u>T.S.(psi)</u>	<u>Y.P.(psi)</u>	<u>% Elong.</u>	<u>Bend</u>
132,400	125,800	11.5	5.0T

B. Test Conditions: After preliminary tests were conducted to narrow down the variables that can be made in the test procedure, the following test conditions were found to be the best for welding of the 6 Al-4V Titanium to 6 Al-4V Titanium:

Explosive:	TRONA 506, aluminized RDX-TNT composition
Explosive Geometry:	1" diameter x 2" high
Explosive Weight:	64 grams, top initiation (for 3" x 3" pcs.) 24 grams, top initiation (for 1" x 3" pcs.)
Etchant:	Concentrated hydrochloric acid on surfaces to be welded for 2 minutes
Temperature:	Material heated to 300° F. prior to test
Medium and Stand-off:	Water; 1/2" between explosive base and metal
Clearance between Metal Sheets:	Metal sheet placed on top of another metal sheet. Clearance between sheets averaged .005"
Set-up:	See Figures 1, 3, and 4.

C. Test Results: Metallurgical analysis of the welds of 6 Al-4V Titanium to 6 Al-4V Titanium was as follows:

Metallographic Examination: This examination was similar to that performed on the 4340 steel weldments. Again, the periphery showed welding, while the central portion had intimate contact. Photomicrograph of the material and the welded interface are shown in Figures 7 and 8. The thin white layer in this material was more uniform in thickness than that in the 4340 interface. The thickness of this interface was between .0002" and .0003".

Bend Tests: The 3" x 3" specimens when bent 180° flat showed no evidence of separation.

Hardness: A microhardness survey of a section through the welded area indicated the interface or welded area to be harder than the base material. The hardnesses follow:

<u>Location</u>	<u>Hardness, VPN</u>	<u>Converted Rockwell "C" Hardness</u>
Anywhere before test	296	29
Near one face	336	34
.005" away	336	34
.010" away	351	35
.015" away	366	37
.020" away	351	35
Welded interface	644	57
.025"	336	34
.030"	366	37
Near second face	336	34

The reading of 644 VPN at the weld area is equivalent to a 57 Rockwell "C" converted, or slightly over 300,000 psi tensile strength converted. It should also be noted that an increase-equivalent of at least 4 points of Rockwell "C" was attained in the metal by the explosive shock or treatment to the metal.

Tensile Shear Tests: Tensile shear tests were conducted on strips 1" wide with a 1" overlap. The total length of each specimen was 5". Under tensile loads, all specimens broke in the region adjoining the overlap and never at the welded joints. This indicated that the welds were stronger than the parent metal, and that the region adjoining the overlap was weakened during explosive tests, (primarily during thinning while welding and not as a heat-affected-zone). Visual examinations of welded strips confirm this fact, and indicate a reduction in thickness of about 10%. The three tensile tests conducted produced the following results:

<u>6 Al-4V Ti Specimen</u>	<u>Failure Load (lbs.)</u>	<u>*Ultimate Tensile Strength (psi)</u>
25C	1705	85,200
26C	2900	145,000
27C	2280	114,000

*These values are based on a .020"-thick specimen. Since some thinning occurred at the failure zone, more accurate tensiles would be higher than those shown.

V. WELDING OF MOLYBDENUM TO 310 STAINLESS STEEL

A. **Material:** These explosive welding tests were conducted on 3" x 3" sections. The molybdenum was .020" thick and the 310 stainless was .025" thick, making a sandwich of .045" thickness. The molybdenum was supplied by General Electric and was the 1/2% titanium, deoxidized arc-cast alloy. The 310 stainless steel was supplied by Ulbrich Stainless Steels, Inc. The chemical and physical properties follow:

Molybdenum, 1/2 Ti

<u>Mo</u>	<u>Ti</u>	<u>T.S.(psi)</u>	<u>Hardness Rockwell "B"</u>
99.5%	0.5%	105 - 120	70

310 Stainless Steel

<u>C</u>	<u>Mn</u>	<u>P</u>	<u>S</u>	<u>Si</u>	<u>Cr</u>	<u>Ni</u>	<u>Fe</u>
.25	2.0	.04	.03	1.5	25	20	Bal.
<u>T.S. (psi)</u>		<u>Y.P. (psi)</u>		<u>Elong. %</u>		<u>Hardness Rockwell "B"</u>	
95,000		45,000		45 - 50		85	

B. Test Conditions: Test conditions were varied with the following being those that resulted in weldments:

Explosive:	TRONA 509, aluminized RDX-TNT composition
Explosive Geometry:	2" diameter x 1" high
Explosive Weight:	100 grams
Etchant:	Aqua regia-cupric chloride solution for 2 minutes
Medium and Stand-off:	Chipboard and a .020" sheet of steel, totaling 1".
Clearance between Metal Sheets:	Averaged .005"
Set-up:	See Figures 1, 3, and 4.
Temperature:	300°F.

C. Test Results: Although no metallographic tests were conducted, the materials were welded together and passed the 180° bend test. Materials could not be separated without tearing the metal. This always indicates a good weldment.

VI. WELDING OF MOLYBDENUM TO MOLYBDENUM
AND B120 VCA TO B120VCA TITANIUM

A. Molybdenum to Molybdenum: The molybdenum under test was the 1/2% titanium arc-cast material and cracked into many vein-like cracks upon welding impact. Of the numerous tests conducted, only two samples had partial welds, and those were at 600° F., and had many, many cracks. This combination was not considered successful, although tests did indicate that some explosive welding can take place.

B. B120 VCA to B120 YCA Titanium: The B120 VCA titanium under test was the hot-rolled, annealed, all-beta alloy of titanium having a tensile strength of 137,000 psi and a yield strength of 132,500 psi.

Of the numerous tests conducted in this series, again only slight success of edge-bonding was achieved on a few samples. This was a most difficult combination to weld explosively. Data did indicate that the possibility of welding this material does exist. Many of the specimens had "burned" spots or areas which indicate the start of welding.

VII. DISCUSSION

Although many parameters were studied in this program of explosive welding, it is felt that the success achieved was worth the efforts. Explosive welding, and particularly that of high-temperature materials, is the most challenging of all the fabricating processes that can be accomplished through explosive forces. Some of the data would defy conventional thinking and thereby create another avenue of attack for meeting the objectives. An example of this is that the pressure (controlled by stand-off and medium) was critical on many of the weldments, i.e., a higher or lower pressure would not create a weldment. The fact that the parameters involved are non-linear has made this a most interesting though difficult program. Results have shown that good weldments of alloy steel, titanium, and dissimilar alloys can be achieved with proper techniques. It is most unfortunate that lack of funds has resulted in the non-completion of all the original test combinations. Various welding parameters are discussed in reference (a) and are graphically shown in Figure 9.

The first published report on explosive weldments was made in reference (b) by Steel Magazine. Additional exploratory work conducted by Canadian Armament Research and Development Establishment, Naval Ordnance Test Station, Stanford Research Center, and National Northern has been mentioned in references (c), (d), (e), and (f) respectively. All of these weld tests discussed were on the aluminums, stainless, coppers, or plain steels and were exploratory in nature.

VIII. CONCLUSIONS

A. Alloy steel (4340 to itself), titanium alloy (6 Al-4V to itself), and dissimilar alloys (Molybdenum to 310 Stainless Steel) were welded through the use of explosive forces. All material was in the .020" to .040" thickness and in annealed conditions. All of the welds were lap-type and were as strong as the parent metals. Weldment interfaces were .0002" to .0003" thick on the titanium alloys and .0002" to .002" thick on the 4340 steel. The weldment was always much harder than the parent metal.

B. Other high-temperature metal combinations, B120 VCA Titanium to itself and Molybdenum to itself, have shown indications of partial welding or burning (start of a weldment) under certain explosive test conditions. Additional research would be needed to determine explosive-welding parameters for these combinations.

IX. RECOMMENDATIONS

It is recommended that the Air Force research groups pursue the study of explosive welding of the high-temperature metals or alloys and also determine the conditions required for welding the various alloys and the effect of known variables.

There will be areas or problems that will require welding of these materials as the military finds more and more need for utilizing "space" or high-temperature materials. It would be beneficial to have this research work pursued if the military and industry are to meet the new fabricating problems brought on by the new "space" alloys.

X. REFERENCES

- a. ASTME Technical Paper 350, Vol. 61, Book 1, "Welding, Forging, and Cutting with Explosives", May 1961, V. Philipchuk
- b. Steel, August 25, 1958, "Explosive Forming Space Age Shapes", Ross Whitehead
- c. Metal Progress, January 1960, "Explosive Forming in Canada", H. P. Tardif
- d. NAVORD Report 7033, Feb. 1960, "The Explosive Working of Metals", John Pearson
- e. ASTME Technical Paper SP60-161, March 1961, "Explosive Welding", D. E. Davenport and G. E. Duvall
- f. ASME Technical Paper 60-MD-4 of May 1960, "Metal Fabrication by Explosives", V. Philipchuk

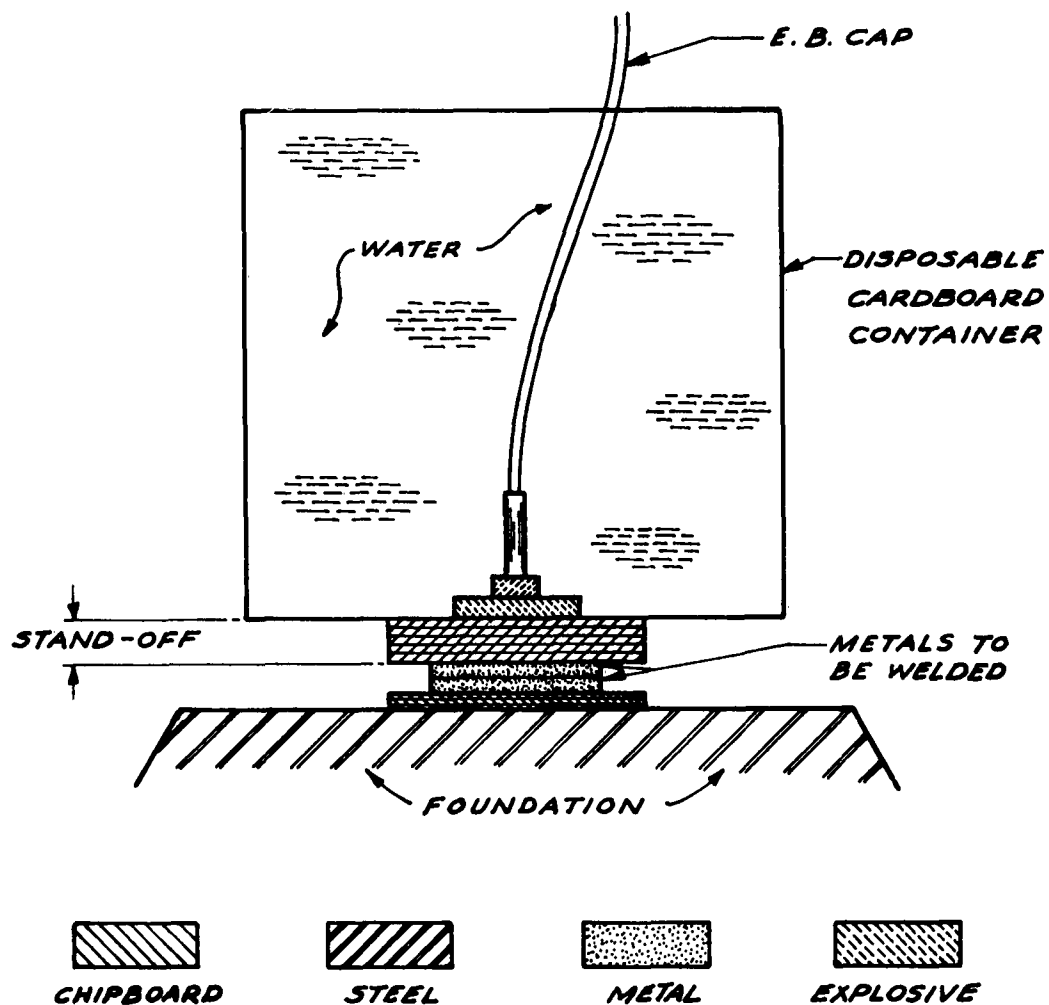


FIGURE 1. TOP INITIATION FOR EXPLOSIVE WELDING.

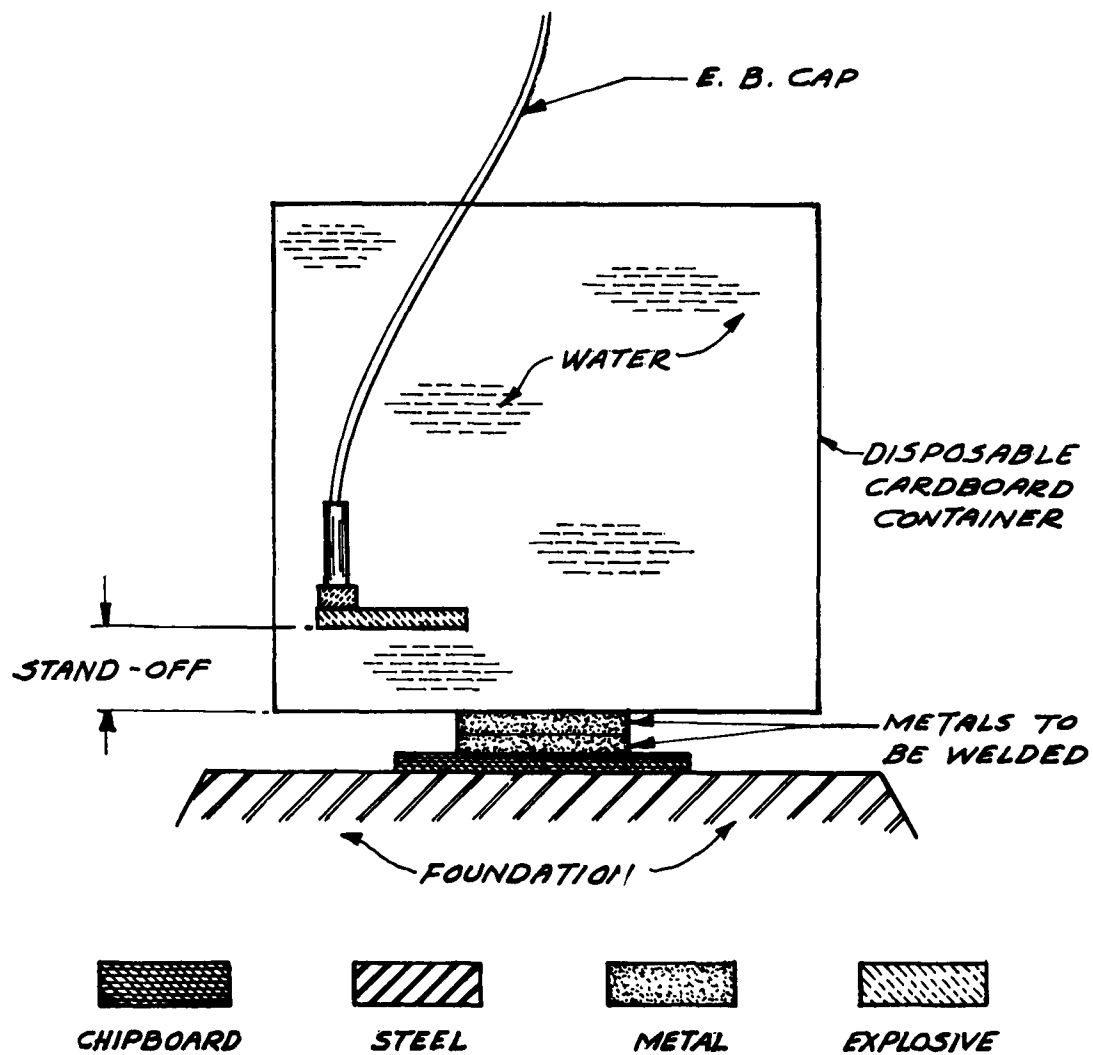


FIGURE 2.- END INITIATION FOR EXPLOSIVE WELDING.

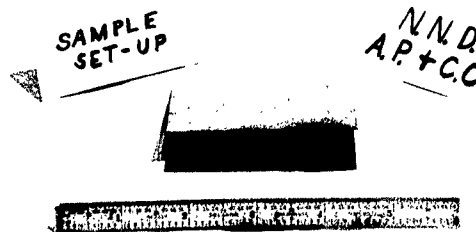


Figure 3. Sheet Metal Set-up For Welding

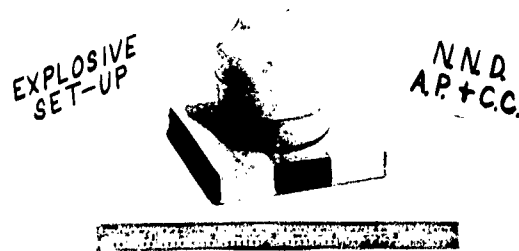


Figure 4. Explosives Set-up for Welding

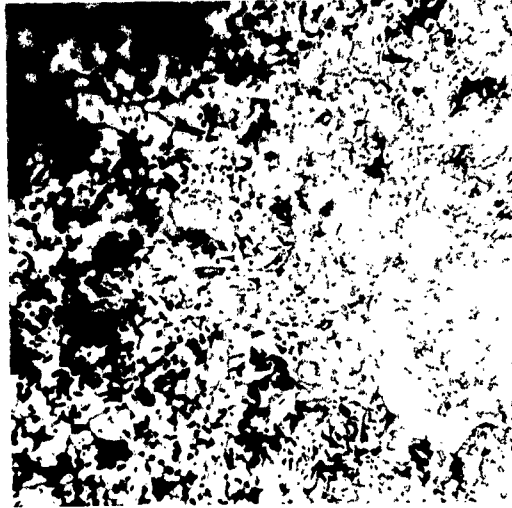


Figure 5. 4340 Steel Weld Photomicrograph, 1000X

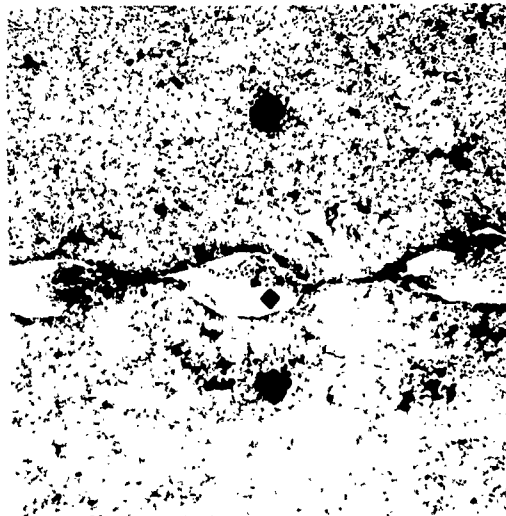


Figure 6. Welded Interface of 4340 Steel, 200X

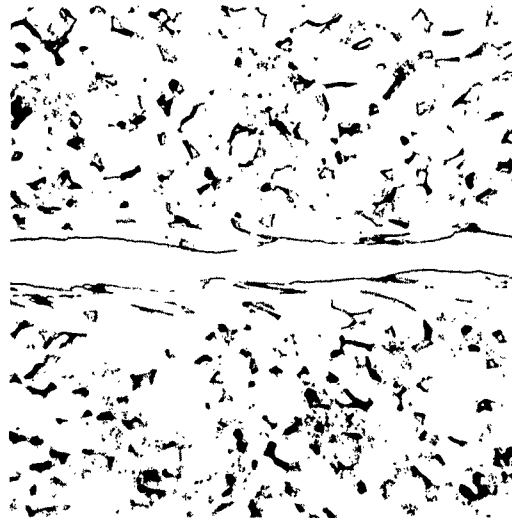


Figure 7. Welded Interface of 6Al-4V Titanium To 6Al-4V Titanium, 1000X

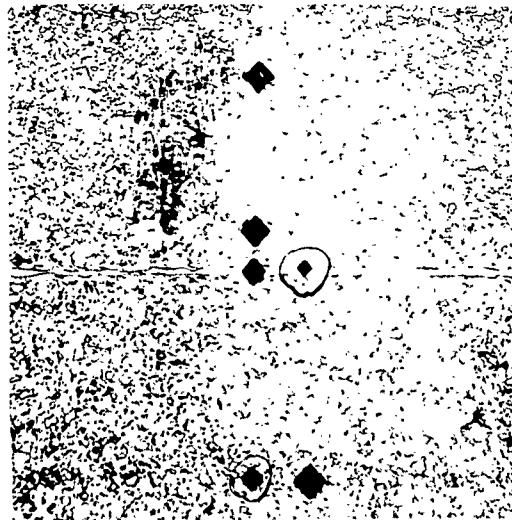
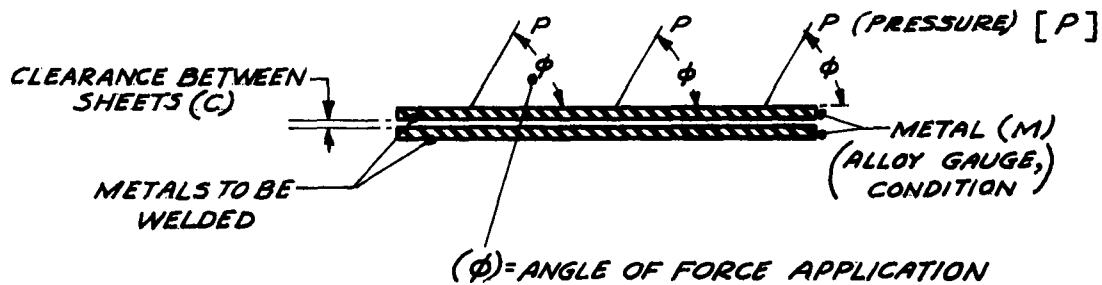


Figure 8. Welded Interface of 6Al-4V Titanium to 6Al-4V Titanium, 200X



$$W = f \left[\frac{M (\tan \phi) P}{C} \right]$$

M = CONSTANT FOR PARTICULAR ALLOY, GAUGE, AND PHYSICAL CONDITION.

ϕ = ANGLE OF FORCE APPLICATION.

P = PRESSURE ON SURFACE OF METAL.

C = CLEARANCE BETWEEN SURFACES.

WHEN $W = \sim 1$, WELDMENT IS CONSIDERED SUCCESSFUL.

FIGURE 9. - PARAMETERS OF EXPLOSIVE WELDING.

NATIONAL NORTHERN DIVISION, American Potash & Chemical Corporation, West Hanover, Mass. EXPLOSIVE WELDING, by Vasil Philipchuk, Aug. 1961. 15p. incl.illus.tables.(Proj.7351; Task 7351b)(ASD TR 61-124)(Contract AF33(616)-6797) Unclassified report Methods were developed for the successful welding by the use of explosive forces of 4340 Steel to 4340 Steel, 6 Al-4V Titanium to 6 Al-4V Titanium, and Molybdenum to 310 Stainless Steel. No success was achieved with B120 VCA Titanium to B120 VCA Titanium and Molybdenum to Molybdenum. Test specimens were in sheet or strip form. All welds were lap-type, with one piece of (over)	UNCLASSIFIED	UNCLASSIFIED
metal directly over or lapped over the other. Successful welds of the above three metal combinations indicate that explosive forces can be utilized for lap weldments of sheet metals when the proper test parameters and techniques have been investigated and developed.	UNCLASSIFIED	UNCLASSIFIED