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TECHNICAL REPORT

72-34-GP

EXPLOSIVE FORMING OF M-1 HELMETS

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Ryan Aeronautical Company

Contract DA19-129-QM-1540

24 July 1961

General Equipment & Packaging Laboratory

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13. ABSTRACT

The work accomplished ~~on this project~~ indicates that it is possible to form helmet like shapes from manganese complex titanium alloy using explosive forming.

At the present state of development, the slow and costly process of explosive forming appears impractical as a means of mass-production of helmets. As described in the technical portion of this report, several shots, with the time required for positioning, charging, and cleaning, are required to form the part without splitting or wrinkling.

Although not within the scope of this contract, a preform was made using the differential forming technique. Even under the adverse conditions of a jury-rig setup, the part was formed with a minimum amount of thinning and without wrinkles.

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high temperature	10					
applications			8			
fabrication			4			
tests					8	
differential pressure					6	
sizing			4		7	
finishing			4		7	

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U. S. ARMY NATICK LABORATORIES

Natick, Massachusetts 01760

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SECTION I INTRODUCTION

1.1 In accordance with Contract DA19-129-QM-1540, Ryan Aeronautical Company, San Diego, California, has applied explosive forming techniques to the fabrication of M-1 helmets as specified in Quartermaster Corps Drawing 2-1-88 with exceptions as noted in the contract. To accomplish the above, Ryan developed techniques for elevated temperature forming of titanium alloy which prove this method of forming is possible. However, due to the number of shots required and the difficulties of handling the forming media, a more practicable method, preforming by a differential temperature forming technique and final sizing and finishing with explosive forming, is described in the conclusions.

1.2 This final report contains detailed data on materials, equipments and techniques; results of various material tests and inspections, a summary of the monthly progress reports, a summary of conclusions and recommendations for continued study.

1.3 None of the materials, techniques or equipments used by Ryan in this study are infringing on unexpired patents or considered proprietary data by Ryan.

1.4 Portions of the Statement of Work contained in the contract, which are applicable to this report, are as follows:

A. <u>SCOPE</u>. Ryan shall supply, commencing 15 January 1960 and continuing through 24 June 1961, the necessary personnel, facilities, tools and materials and do all other things necessary for and incident to the performance of the work set forth below. Ryan agrees to use its best effort in the performance of this contract.

1. Apply explosive forming techniques to the fabrication of the M-1 Helmet Shell specified in Quartermaster Corps. Drawing No. 2-1-88 except that:
    a. Ryan will use this drawing to establish a line 0.044 inch inside the solid line of this drawing. This will be the inside contour of the helmet shell, and the die Ryan produces will be o.075 inch larger than this inside contour. This die shall be used for both the 0.075 inch and the 0.100 inch material.
    b. The starting blank thickness shall be as near 0.075 inch and 0.100 inch as practicable with commercial tolerances applicable.
2. Consideration shall be given to techniques developed so that they may have the greatest potential of being economical for large quantity production and competitive with other conventional processes, such as deep draw.
3. The following general objectives shall be applicable:
    a. Ambient and, if necessary, elevated temperature forming shall be explored with development of the lowest practicable and economical forming temperature as primary objective.
    b. Tooling shall be simplified to the maximum practicable extent.
    c. Scrap rate shall be as low as possible in view of high material costs.
    d. The minimum number of forming steps, intermediate anneals, etc., shall be attained.
    e. Except for the visor area, where it is expected that the formed thickness may approximate the original blank thicknesses of 0.075 inch or 0.100 inch as applicable, thickness uniformity shall be maintained throughout the helmet insofar as practicable. Assuming

uniform individual blank thickness, a formed helmet thickness tolerance of plus or minus 0.002 inch in the above area shall be the objective.

f. Inasmuch as embrittlement from all sources may lower ballistic values, processing techniques shall be selected so as to either avoid embrittlement during processing or provide for acceptable removal of embrittlement after fabrication.

4. a. The 3 percent Mn Complex plus 4 percent Titanium alloy shall be used in this development and shall meet the following:

Mechanical Properties (Fully annealed)	
Ultimate Tensile Strength (PSI)	150,000 - 160,000
Yield Strength (PSI)	135,000 - 145,000
Elongation (percentage in inches)	15 - 20

Chemistry

Mn	2.5 - 3.3
Fe	0.85 - 1.15
Cr	0.85 - 1.15
V	0.85 - 1.15
Mo	0.85 - 1.15
Al	3.5 - 4.5
Total Alloy	9.5 - 12.5

b. Proposed deviations from the above shall be subject to the approval of the Contracting Officer.

c. Material heat number, certified chemical analysis and certified mechanical properties, shall be furnished the Government.

d. The services of the Department of Defense, Defense Metals Information Center at Battelle, will be available to both the mill and the Contractor upon direct request of the Contractor in establishing optimum ballistic and formability processing and fabricating procedures.

5. Two 14 1/2 inch by 11 3/4 inch panels of each heat of 0.075 inch and 0.100 inch material used for development purposes shall be furnished the Government for ballistic and other tests.

6. a. Upon successful development of explosive forming techniques for the specified thicknesses, representative samples of titanium explosive formed into helmet-like shape will be furnished the Government for examination.

TABLE 1

Alloy	Thickness Inches	Condition	Number Helmet-Shaped Samples
3 % Mn Complex + 4Al	0.075	Annealed	5
3 % Mn Complex + 4Al	0.100	Annealed	5
3 % Mn Complex + 4Al	0.075	As Formed	2
3 % Mn Complex + 4Al	0.100	As Formed	2

b. Inasmuch as the ballistic superiority of the alloy selected is based on the fully annealed condition, the final fabricated condition of helmet-shaped samples produced shall approximate this condition as closely as possible.

c. The edge flash shall be trimmed.
d. Helmet-shaped samples shall be identified by appropriate marking, including alloy heat numbers on the visor.

7. A reasonably smooth surface condition shall be obtained which shall be free of nicks, cracks or other points of potential ballistic weakness.
8. Tooling manufactured or acquired for this research with contract funds will become the property of the Government and will be delivered to the Government upon completion of the contract.

B. <u>REPORTS</u>. a. Ryan shall submit twelve (12) copies of a monthly progress report to the Project Officer one month after award of contract and at monthly intervals thereafter within 10 days after each reporting month.

This report shall include the following:

1. Technical progress and future plans.
2. An estimate of the percentage of work completed to date.
3. An estimate of the percentage of estimated costs incurred to date.
4. A statement that to Ryan's best knowledge the costs remaining unexpended are sufficient to complete the work called for by the contract, or a revised estimate setting forth the costs required to complete the contract and the reason (s) for the excess contemplated.

b. Thirty (30) copies of a comprehensive final report shall be submitted to the Project Officer within thirty (30) days after completion of the contract. These reports shall be delivered f.o.b. to the Government addressed to W M R & E Command, Natick, Massachusetts, Attn: Project Officer, Mrs. Helen Agen, Mechanical Engineering Division, Marked: Project Number 7-80-05-001, Contract No. DA19-129-OM.

c. Consideration will be given by the Contractor to the performance of the work called for by this contract in such a manner as to produce end results that are susceptible of reproduction by or for the Government by equipment which is readily available through Government or commercial channels and by standard or proven production techniques, methods and processes. Unless approved by the Contracting Officer, Ryan will not knowingly, in the performance of the work called for by this contract, produce an end result requiring the details of secrets of manufacture, such as may be contained in but not limited to manufacturing methods or processes, treatment and chemical composition of materials, plant layout and tooling, to the extent that such information is not disclosed by inspection or analysis of the product itself or produce an end result requiring the use of a patented process or having incorporated into it any part, component, sub-assembly or combination thereof covered by unexpired patent.

d. Reports shall include metallurgical studies of high strain rates and thermal treatments on typical parts and shall include but not necessarily be limited to the following tests:

1. Microstructural and photomicrographs before and after each forming operation.
2. Hardness survey.
3. Section thickness survey.
4. Crack inspection.

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e. The final report shall include the following:
   1. A complete set of photographs of each step of the development process.
   2. A set of 3 1/4 inch by 4 inch color glass slides in sufficient number to cover the complete development program. The slides shall be suitably identified and numbered. A brief written description shall accompany each slide.

C. DELIVERY.

F. O. B. Destination

Delivery to be accomplished from 15 January 1960 through 24 June 1961.

SECTION II EQUIPMENTS AND MATERIALS USED.

2.1 EQUIPMENT. The following equipment and facilities were used in performing the work required by this project:

a. A controlled explosive forming area.
b. An explosive charge preparation area.
c. A 2-ton crane.
d. A hydraulic holding fixture.
e. Two vacuum pumps
f. Two temperature control units.
g. Analytical scales.

2.2 The explosive forming area is located in the Ryan Aerospace Division plant and isolated from other activities by a sheet metal fence (see figure 1). The explosive charge preparation area is located within the forming area. The hydraulic holding fixture utilized four 20-ton Blackhawk Porta-Power Jacks (see figures 2, 3, and 4). Sim-Ply-Trol temperature control units were used to control the temperatures of the upper and lower sections of the forming equipment. The analytical scales were used in the explosive preparation area for precision measurement of explosives.

2.3 TOOLS. Special tools required for forming the shapes desired consisted of:

a. First stage form die (see figure 5).
b. Second stage form die (see figure 2).
c. Sand Hopper (see figure 2).
d. Apply type check and scribe tool (see figure 7).

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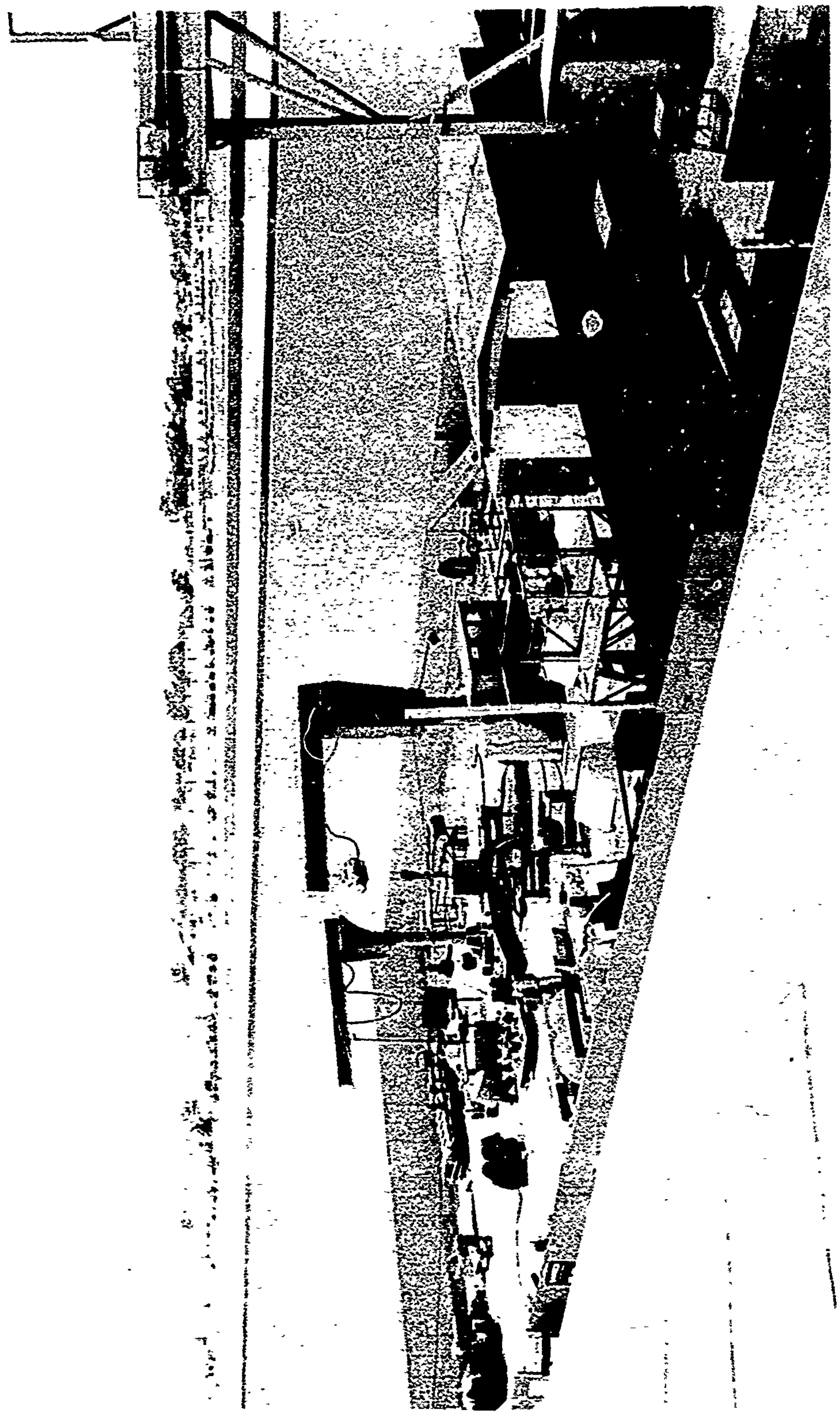

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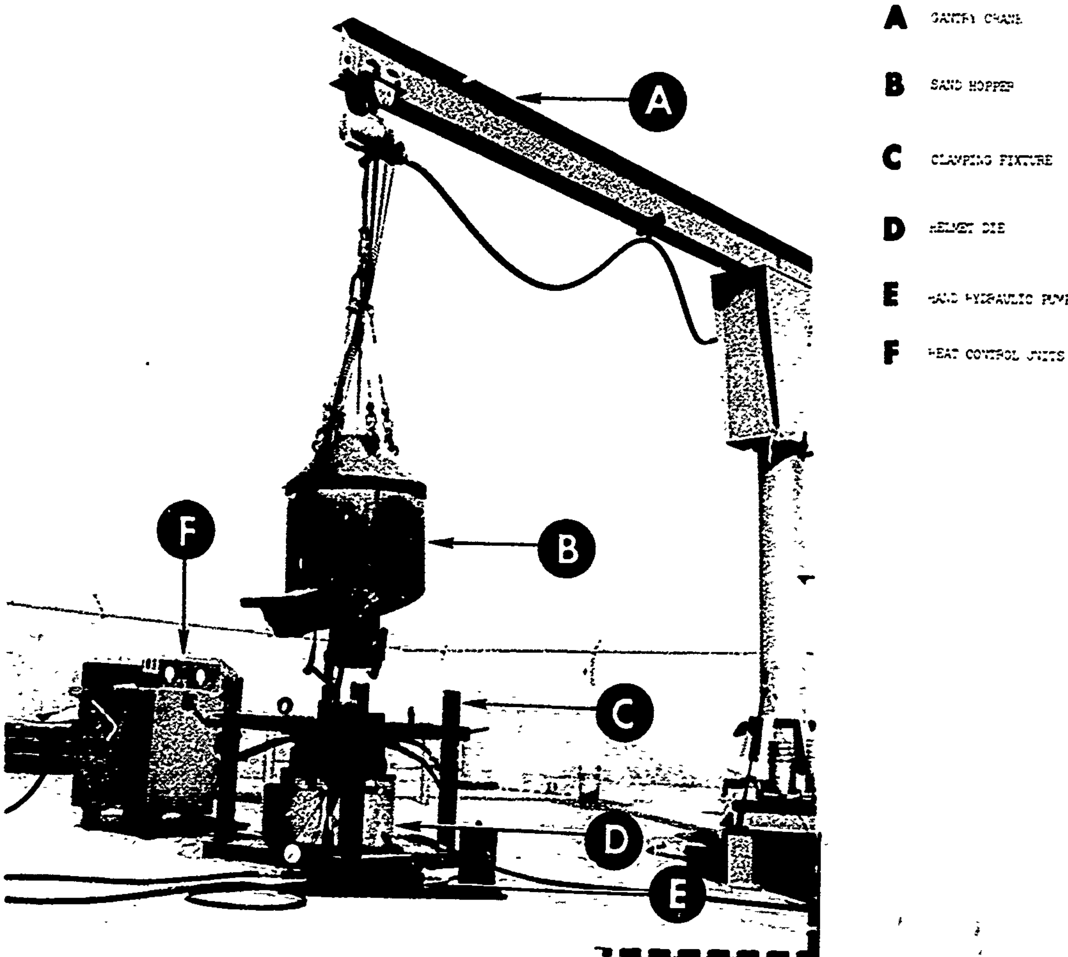
Figure 1. Ryan Engineering Research and Development
On Site-Controlled Explosive Forming Area



ABOVE:
PRIOR TO POSITIONING CHIMNEY
AND SAND HOPPER.

RIGHT:
DURING EXPLOSION OF CHARGE

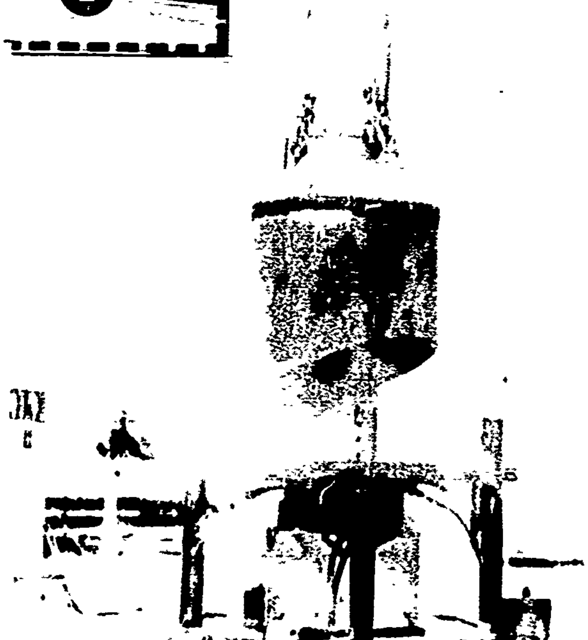
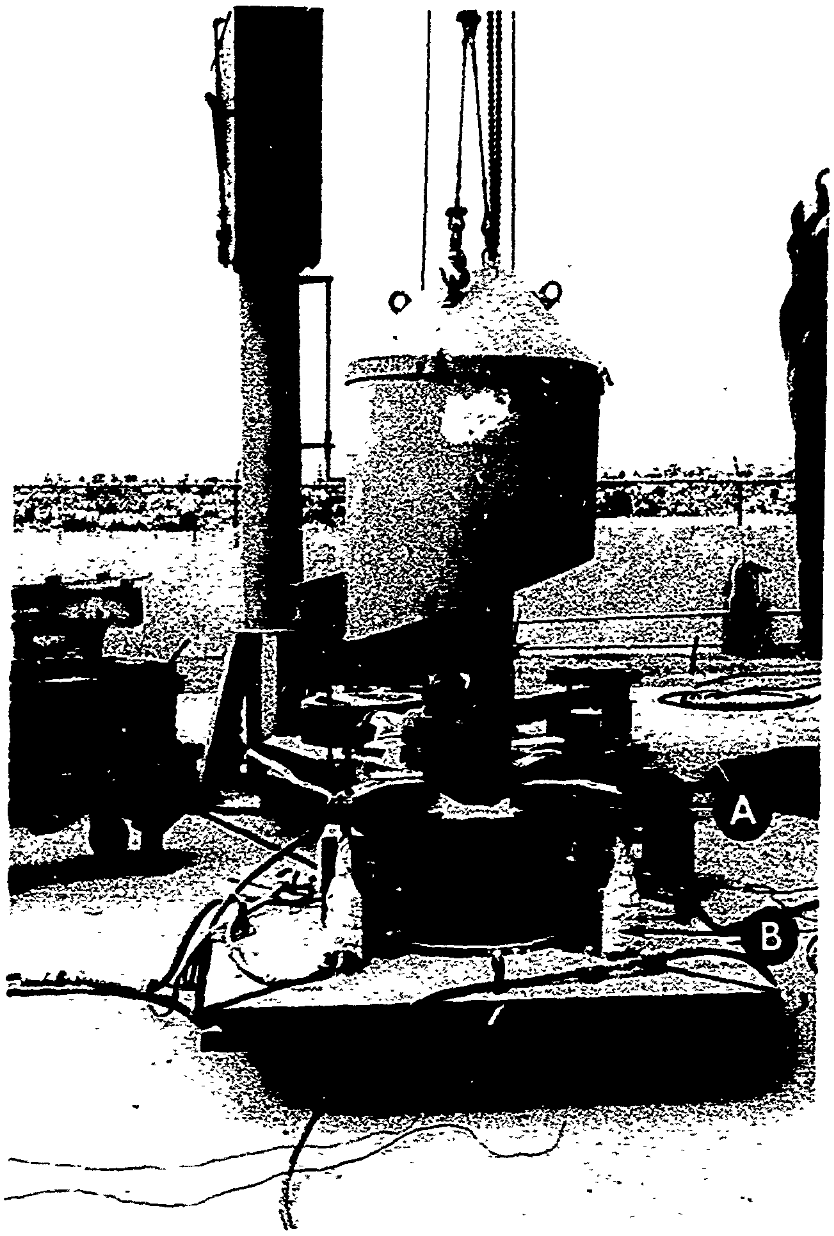


Figure 2. A Complete Explosive Forming Set-up Prior to improving Holding Fixture and Hydraulic Hand Pump



A IMPROVED CLAMPING FIXTURE

B FOUR 20-TON HYDRAULIC JACKS

Figure 3. Improved Explosive Forming Set-up with improved Holding Fixture.

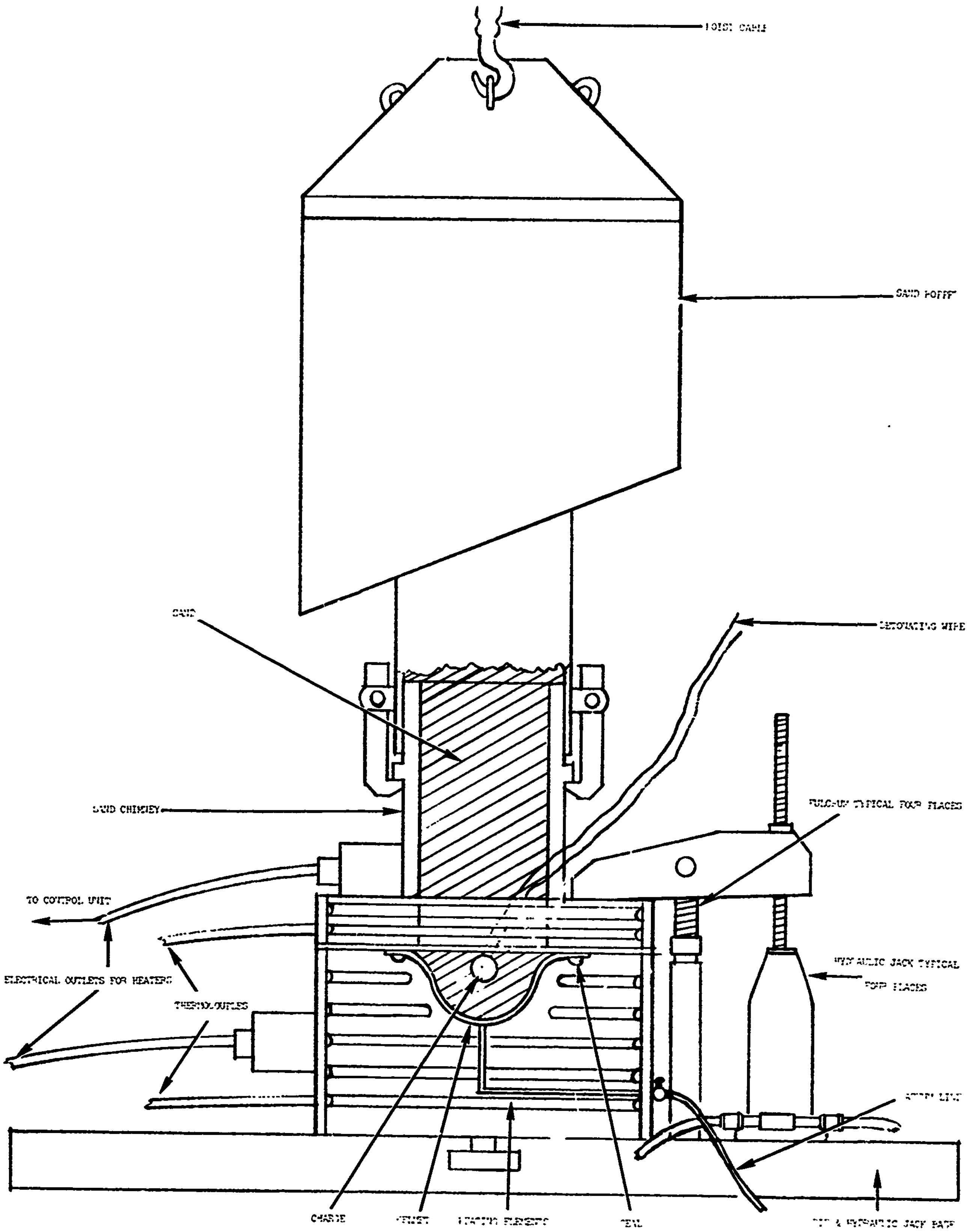


Figure 4. Cross Section of Explosive Forming Set-up Used in Helmet Forming

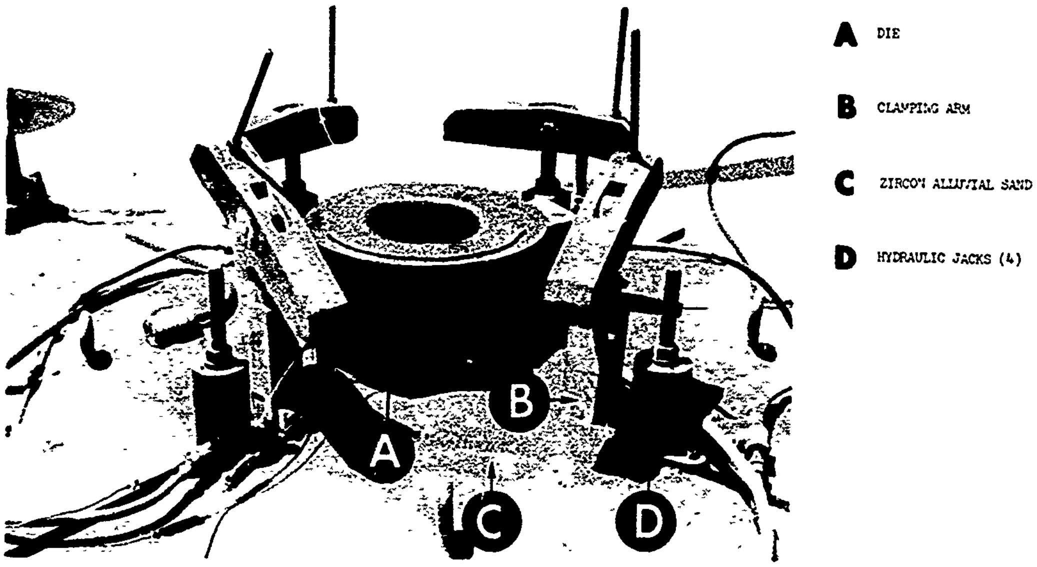


Figure 5. Helmet Formed Through First Stage Die

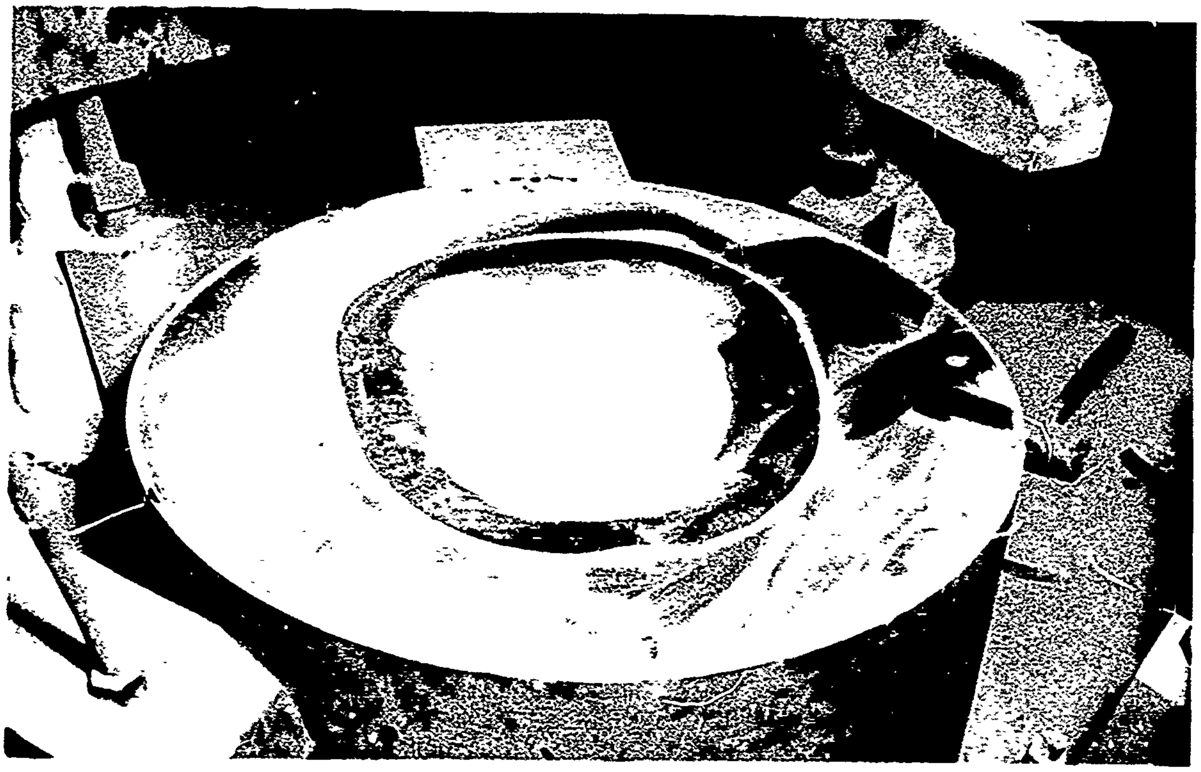
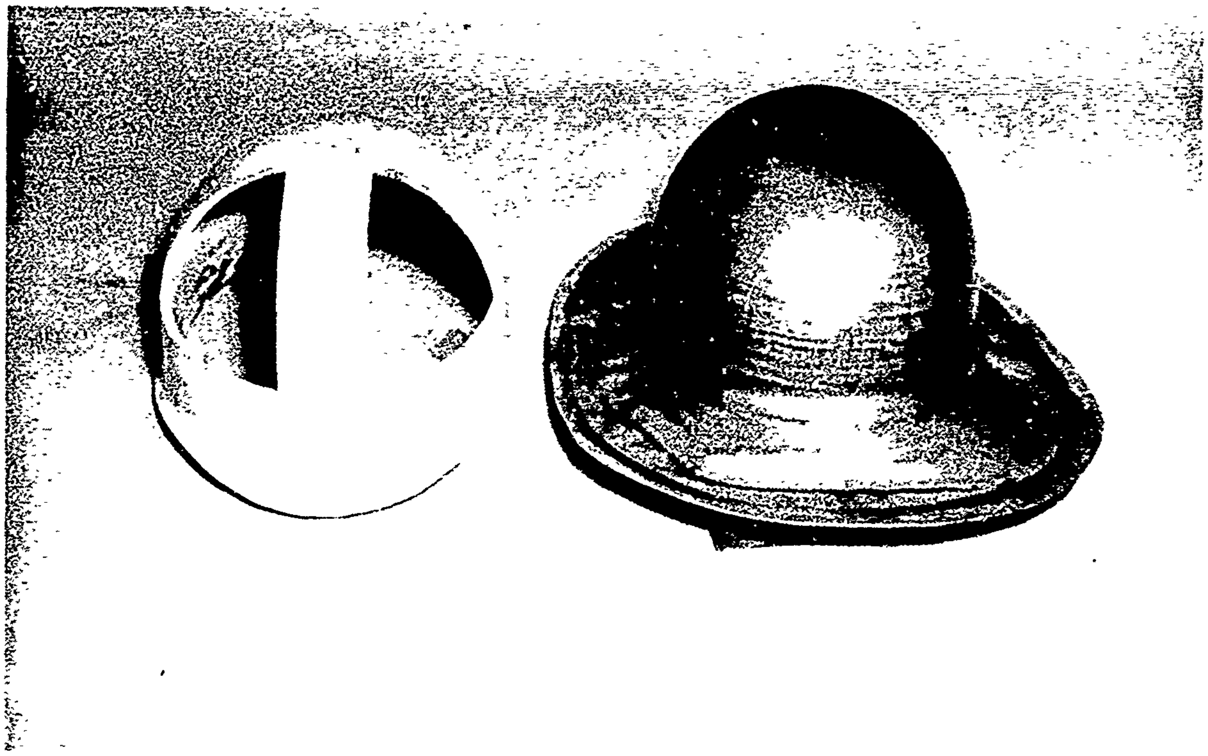


Figure 6. Helmet Formed through Second Stage Die Prior to Removal of Sand.



HELMET AND APPLY-TYPE CHECK AND SCRIBE TOOL

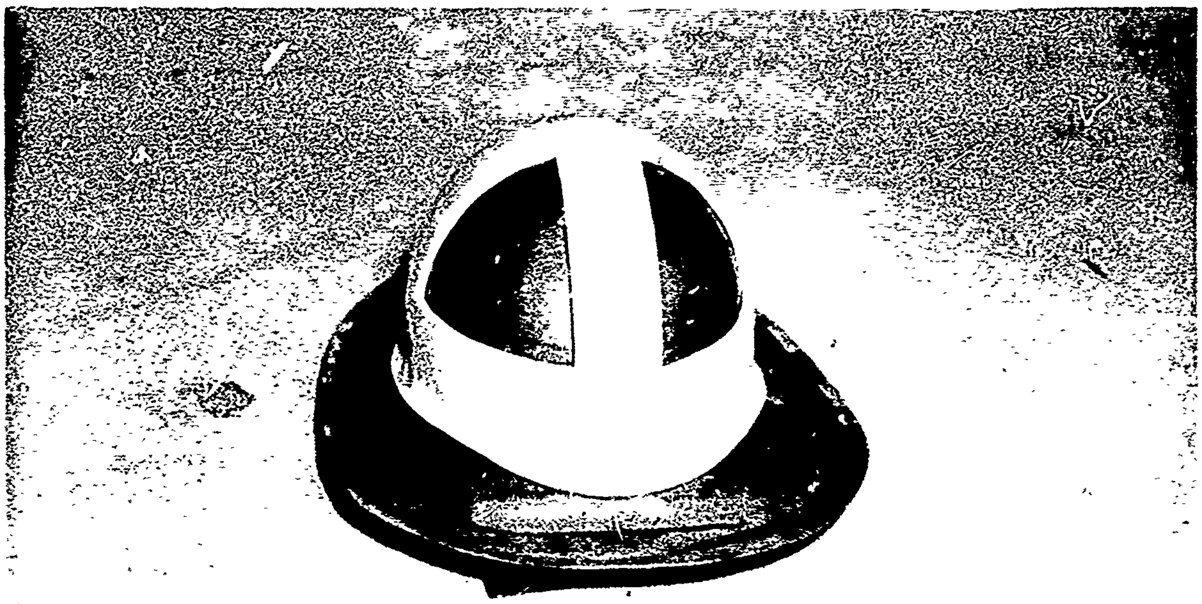


Figure 7. Final Formed Helmet and Apply-Type Check and Scribe Tool.

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SECTION III MATERIALS.

3.1 MATERIALS USED. Since the metallurgical report indicated the manganese titanium complex would require elevated temperature forming, the forming media selected was zircon alluvial sand. The elevated temperatures also required insulating the explosive to prevent pre-ignition. The explosive used was Dupont No. 5066 Pistol Powder in varying quantities dependant on the stage of work. The materials required to prepare an explosive package are shown in figure 8. Figure 9 is a cross section of an explosive package showing the method of insulating. To reduce friction between the flange of the helmet and the die clamp ring, and to prevent surface oxidation of the titanium during heating, several types of lubricant were tried. Everlube T60 seemed to work the best and was used for most of the tests.

3.2 The materials from which the helmets were formed varied slightly from that specified in the contract due to the inability of the vendor to produce titanium alloy precisely as designated. Authorization for the variation was contained in a wire from Commanding General, Quartermaster Research and Engineering Command, U.S. Army, Natick, Massachusetts, dated September 14, 1960. A comparison of the designated material and the material received is provided in figure 10.

3.3 RAW MATERIAL EVALUATION. Tests were run on the raw material to determine the mechanical properties and the formability limitations. These tests included:

1. Tensile Strength. Room temperature tensile properties at slow and fast strain rates.
2. Formability. Room and elevated temperature band tests, hot dimpling tests, elevated temperature uniform elongation limit tests and hot-cold working response determinations. Tests to determine the maximum forming temperature. Tests to improve the bendability of the material.
3. Thickness and Hardness. Thickness and hardness surveys of the raw material.
4. Hydrogen Content. Chemical analysis to determine the hydrogen content.
5. Microstructure and Photomicrographs. Examination of typical sections and photomicrographs of these sections.

3.4 TEST PROCEDURE OF MATERIALS. The test procedure used and the results of the test were as follows:

a. Tensile Tests. Standard A.S.T.M. sheet metal specimens were milled from the material. One specimen of each sheet was tensile tested at a strain rate of approximately 1.4 inches per inch per minute (the maximum strain rate of the stress machine used). The yield strength, ultimate strength and elongation in two inches was determined for each specimen. These tests were conducted at ambient temperature.

The test results are shown in figure 11. The yield strength of the 0.075 inch material averaged 94 percent of the ultimate strength, while the yield strength of the 0.100 inch material averaged 99 percent of the ultimate strength, when tested at the 0.005 inch per inch per minute strain rate.

The yield strength of both the 0.075 inch and the 0.100 inch material was 100 percent of the ultimate strength when tested at the 1.4 inches per inch per minute strain rate.

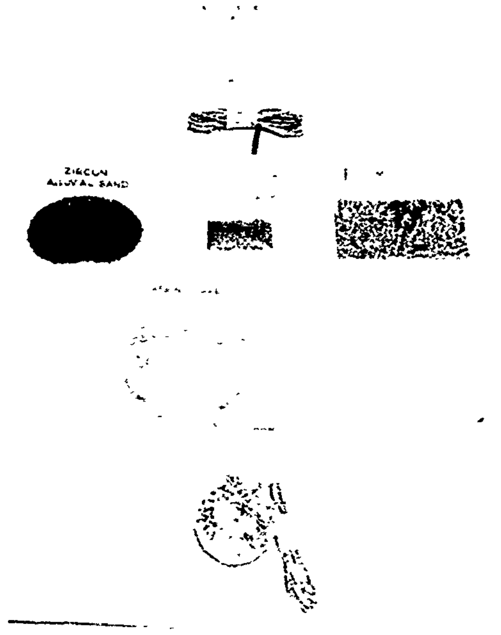

Figure 8. Ingredients Used to Prepare Insulated Explosive Charge.

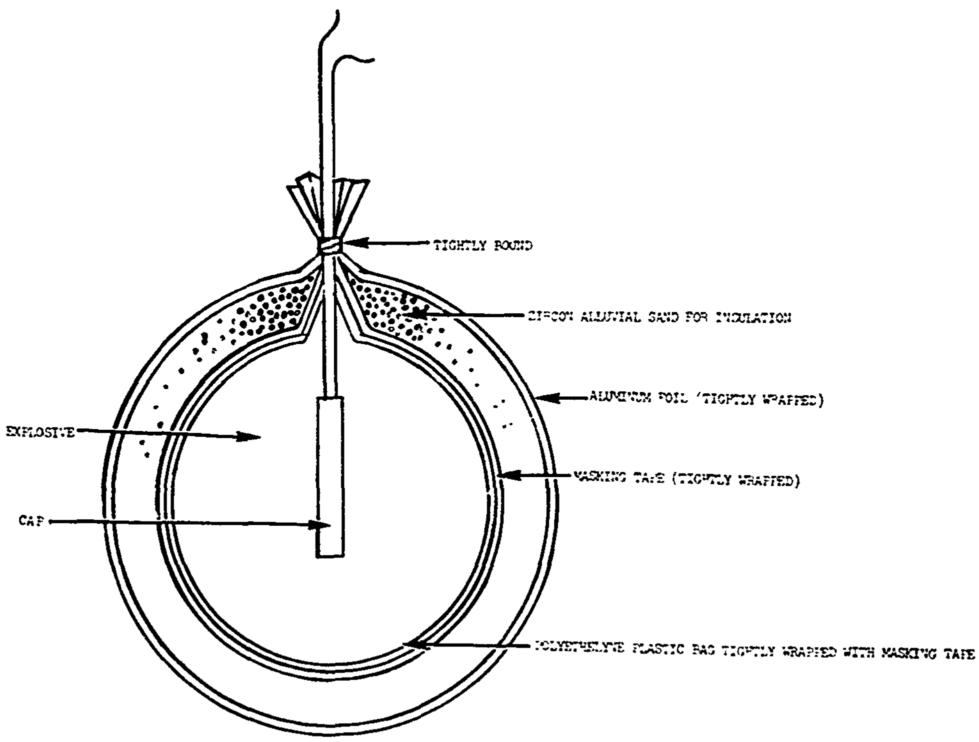

Figure 9. Cross Section of Insulated Explosive Charge.

	MATERIAL ORIGINALLY DESIGNATED	MATERIAL "AS-RECEIVED"			
		HEAT NO. XT-70021	HEAT NO. XT-70022	HEAT NO. XT-70023	HEAT NO. XT-70024
CHEMISTRY					
Mn	2.5 - 3.3	4.50	3.00	2.50	2.30
FE	0.85 - 1.15	1.18	1.15	1.21	1.11
Cr	0.85 - 1.15	1.05	0.94	1.13	0.94
V	0.85 - 1.15	1.09	1.08	1.15	1.07
Mo	0.85 - 1.15	1.23	1.19	1.14	1.21
AL	3.5 - 4.5	4.05	4.12	4.17	4.13
TOTAL ALLOY	9.5 -12.5				
MECHANICAL PROPERTIES (FULLY ANNEALED)					
ULTIMATE TENSILE STRENGTH(PSI)	150,000 - 160,000	148,000	150,500	142,820	151,620
YIELD STRENGTH(PSI)	135,000 - 145,000	143,200	138,890	135,900	147,500
ELONGATION (% in 2 INCHES)	15 - 20	15	15	16	12
GAGE		0.100	0.075	0.075	0.100
ROCKWELL HARDNESS		36C	36C	36C	36C

Figure 10. Chemical and Mechanical Analysis of Titanium Sheet Material

LOT NO.	SHEET NO.	GAGE INCHES	TEST RESULTS FOR LOW STRAIN RATE - 0.005 INCHES PER INCH PER MINUTE				TEST RESULTS FOR HIGH STRAIN RATE - 1.4 INCHES PER INCH PER MINUTE			
			YS K/SQ. IN.	TS K/SQ. IN.	YS/TS	%ELONG/2IN.	YS K/SQ. IN.	TS K/SQ. IN.	YS/TS	%ELONG/2IN.
0304	IV	0.100	142	[illegible]	1.00	10.0*	146	146	1.00	8.5*
0304	2V	0.100	142	142	1.00	11.0*	145	145	1.00	11.0*
0304	3V	0.100	146	148	0.99	10.5*	146	146	1.00	7.0
0305	1V	0.100	153	153	1.00	10.5*	151	151	1.00	8.0*
0305	2V	0.100	154	154	1.00	10.0*	151	151	1.00	10.0*
0305	3V	0.100	153	153	1.00	10.5*	149	149	1.00	10.5
0306	1V	0.100	134	145	0.92	14.5	147	147	1.00	13.0
0307	1V	0.075	136	145	0.94	14.5	145	145	1.00	13.5
0307	2V	0.075	134	143	0.94	15.0	145	145	1.00	14.0*
0307	3V	0.075	135	143	0.94	15.5	146	146	1.00	11.0*
0308	1V	0.075	141	150	0.94	15.5	152	152	1.00	13.5
0308	2V	0.075	141	150	0.94	14.5	153	153	1.00	13.0
0308	3V	0.075	141	150	0.94	13.5	153	153	1.00	13.5
0308	4V	0.075	141	149	0.95	14.0	154	154	1.00	13.0

*FRACTURED OUTSIDE OF GAGE MARKS.

Figure 11. Tensile Test Results.

LOT NO.	SHEET NO.	GAGE	TEST RESULTS FOR FIRST SAMPLE	TEST RESULTS FOR SECOND SAMPLE
0304	1V	0.100	FAILED AT 105° (Center 1/2)	FAILED AT 105° (CENTER 3/4)
0304	2V	0.100	FULLY FORMED, NO FAILURE	FAILED AT 105° (CENTER 3/4)
0304	3V	0.100	FULLY FORMED, NO FAILURE	FAILED AT 90° (TWO PIECES)*
0305	1V	0.100	FULLY FORMED, NO FAILURE	FULLY FORMED, NO FAILURE
0305	2V	0.100	FULLY FORMED, NO FAILURE	FAILED AT 90° (TWO PIECES)*
0305	3V	0.100	FAILED AT 60° (TWO PIECES)*	FULLY FORMED, NO FAILURE
0306	1V	0.100	FAILED AT 90° (TWO PIECES)*	FAILED AT 60° (TWO PIECES)*
0307	1V	0.075	FULLY FORMED, NO FAILURE	FULLY FORMED, NO FAILURE
0307	2V	0.075	FULLY FORMED, NO FAILURE	FULLY FORMED, NO FAILURE
0307	3V	0.075	FULLY FORMED, NO FAILURE	FULLY FORMED, NO FAILURE
0308	1V	0.075	FULLY FORMED, NO FAILURE	FULLY FORMED, NO FAILURE
0308	2V	0.075	FULLY FORMED, NO FAILURE	FULLY FORMED, NO FAILURE
0308	3V	0.075	FULLY FORMED, NO FAILURE	FULLY FORMED, NO FAILURE
0308	4V	0.075	FAILED AT 90° (TWO PIECES)*	FULLY FORMED, NO FAILURE

BEND RADIUS 3.1T
*BEND ANGLE APPROXIMATE AT FAILURE.

Figure 12. Ambient Temperature Bend Test Results for Raw Material.

The low yield-to-ultimate strength spread would indicate a material of relatively low formability. The material was sensitive to strain rate, as demonstrated by the increase in the yield-to-ultimate strength ratio.

The trend was for the material to fracture near the end of the test section. This might indicate a tendency toward notch sensitivity.

b. Formability. Bend test samples were obtained for the as-received material. These samples were one by two inches in size. A titanium alloy of this type will normally bend 105 degrees over a bend radius of from 3T to 5T. The radius used for these tests was 3.1T. These samples were bent at ambient temperature in a brake until the unloaded bend angle was 105 degrees or until the sample failed.

The ambient temperature bend test results are shown in figure 12. Note that samples from the 0.075 inch material generally were capable of bending 105 degrees over the 3.1T bend radius and that samples from the 0.100 inch material generally were not capable of bending 105 degrees over the 3.1T radius. This behavior led to the suspicion that the material might contain an embrittled surface layer. The bend tests run on the chem-milled samples were used to investigate this premise.

c. Chem-Mil. Four one inch by two inch bend test samples of 0.100 inch material were chem-milled to remove a suspected embrittled surface layer. About two to three mils were removed from each side of the samples. Four additional samples, not chem-milled, were held as control samples. Each sample was bent to 105 degrees over a 2.7T radius. The samples which formed satisfactorily were re-formed to 115 degrees over a 2.0T radius.

The bend test results for the chem-milled samples are shown in figure 13. Three of the control samples broke into two pieces at a small bend angle, and the fourth control sample developed a small crack at 105 degrees when bent over the 2.7T radius. All of the chem-milled samples bent satisfactorily to 105 degrees over a 2.0T radius. When the chem-milled samples were reformed to 115 degrees over a 2.0T radius, two of the samples developed a crack in the center three-fourths of the sample at about a 110 degree bend angle. The chem-milled samples did not fail in a catastrophic fashion, as did the control samples, thus indicating a lower notch-sensitivity and presumably a lesser amount of surface contamination. Figure 14 provides further data on bend test results for materials before and after chem-milling.

d. Heating. Elevated temperature bend tests were run using two by four inch samples taken from a single piece of 0.075 inch material. The tests were performed using an integrally heated die (of a form die design) containing a 5/32 inch radius punch (2.0T for this material thickness) and a 105 degree bend angle. This die was mounted in a power brake, heated and the proper die clearance obtained. Forming was accomplished by placing the sample on the die, bringing the punch into contact with the sample for several minutes, and then closing the die. In some instances, the die was held in the closed position, while in other instances, the sample was removed immediately after forming was complete. The samples were visually checked for any signs of cracking. The final bend angle and radius were measured. The results for the elevated temperature bend tests are shown in figure 15. Note that when a temperature of 1000 degrees F or above was used, the tendency toward cracking was eliminated. With a five minute dwell time after forming, the spring-back was at a minimum. Without a final dwell, the spring-back was at a minimum at temperatures of 1050 degrees, 1100 degrees, and 1150 degrees F, but was greater than the springback obtained when a final dwell was used. The bend radius, for all of the samples which were successfully formed, was very close to the punch radius.

f. Dimpling. Hot dimpling tests were run on samples taken from a single sheet of 0.075 inch material. A dimpling die for a No. 10 screw was used. Forming was accomplished by heating the die to the test temperature, inserting the pilot hole in the material over the punch, slowly closing the die to allow about one minute of preheat time, and applying the load over a period of about one minute to a value of 4000 PSI. The specimen was then immediately unloaded and removed from the die. Samples were run at 1000 degrees, 1100 degrees, 1150 degrees, and 1200 degrees F. The formed dimples were examined at 40X for signs of cracking.

All of the hot-formed dimples had small, circumferential cracks in the parent material immediately adjacent to the dimple. In addition, the dimples formed at 1000 degrees and 1100 degrees F had circumferential cracks in the dimple proper, near the outer periphery of the dimple. The definition was good in the dimple formed at 1200 degrees F, but became progressively worse as the dimpling temperature was lowered.

g. Elongation. Approximate uniform elongation limit data was obtained using an elevated temperature stress rupture machine. Testing was accomplished by heating the specimen to the test temperature, applying a selected load at a relatively slow rate, removing the load, removing the specimen and measuring the specimen width at the center and near both ends of the test section. The specimen was then re-inserted in the machine and tested at progressively higher loads using the same procedure. The uniform elongation limits were estimated from the results.

The elevated temperature uniform elongation limit results obtained using the stress rupture equipment are shown in figure 16. Note that the elongation is fairly uniform over a two inch gauge length to a value somewhat below ten percent.

h. Stress. The sample stressed at 35,000 PSI at the 1150 degree F test temperature was tensile tested after completion of the uniform elongation limit tests, to determine if any hot-cold working had occurred. A control sample from the same sheet was also tensile tested as a control sample. The ambient temperature tensile

HEAT NO.	SAMPLE NO.	CONDITION	TEST RESULTS FOR 105° BEND - 2.7T RADIUS	115° BEND - 2.0T RADIUS
70021	1	AS REC'D.	FAILED AT 30°(TWO PIECES)*	
70021	2	AS REC'D.	FAILED AT 30°(TWO PIECES)*	
70024	1	AS REC'D.	FAILED AT 105°(SMALL CRACK)	
70024	2	AS REC'D.	FAILED AT 30°(TWO PIECES)*	
70021	1	CHEM-MILL.	FULLY FORMED, NO FAILURE	FULLY FORMED, NO FAILURE
70021	2	CHEM-MILL.	FULLY FORMED, NO FAILURE	FAILED AT 110°(CENTER 3/4)*
70024	1	CHEM-MILL.	FULLY FORMED, NO FAILURE	FAILED AT 110°(CENTER 3/4)*
70024	2	CHEM-MILL.	FULLY FORMED, NO FAILURE	FULLY FORMED, NO FAILURE

* BEND ANGLE AT FAILURE APPROXIMATE

Figure 13. Ambient Temperature Bend Test Results For Chem-milled Vs. As received Material

CONDITION OF MATERIAL	DIRECTION	BEND RADIUS	BEND ANGLE	REMARKS
AS-RECEIVED	X	3.9T	110°	
	Y	3.9T	103°	
AS-RECEIVED & CHEM-MILLED	X	4.0T	105°	
	Y	4.1T	102°	
HEAT-TREATED	X	3.9T		SUDDEN,COMPLETE FAILURE
	Y	3.9T		SUDDEN,COMPLETE FAILURE
HEAT-TREATED & CHEM-MILLED	X	4.0T	102°	
	Y	4.1T	102°	
HOT-FORMED	X	3.7T		SUDDEN,COMPLETE FAILURE
	Y	3.7T		SUDDEN,COMPLETE FAILURE
HOT-FORMED & CHEM-MILLED	X	4.3T	103°	
	Y	4.2T	105°	

NOTES:
1. NO EVIDENCE OF FAILURE EXCEPT AS NOTED.
2. MATERIAL USED - 4Al-3Mn COMPLEX ALLOY - 0.080 IN. THICK.
3. EACH ENTRY IS AVERAGE OF TWO ONE-INCH WIDE SAMPLES.
4. CHEM-MILLING REMOVED AVERAGE OF TWO MILS FROM EACH SIDE.
5. HEAT-TREATED SAMPLES WERE RUN AT 1300° F FOR 30 MINUTES.
6. X AND Y DIRECTIONS ARE NOT NECESSARILY THE SAME BETWEEN GROUPS.

Figure 14. Bend Test Results Under Various Conditions.

test results for the sample previously stressed at 35,000 PSI at a temperature of 1150 degrees F, and the results for the control sample were as follows:

Sample Condition	YS, K/SQ IN.	TS, K/SQ IN.	%ELONG/2 SQ IN
Previously stressed	145	152	12.5
Raw Material	146	150	13.

As may be seen, these results were nearly identical, indicating that no hot-cold working will occur at 1150 degrees F.

The previous tests indicated that a forming temperature of 1200 degrees F or lower will probably be required for this alloy. Tests were run at 1200 degrees F and lower to determine if any reduction in ductility would be encountered due to an aging response. To determine this, samples from the as-received material were heated for 90 minutes at various potential forming temperatures and air cooled. In addition, a second such group was also held for 16 hours at 850 degrees F to determine if solution heat treatment would occur at any of the potential forming temperatures. The samples were then tensile tested.

i. Aging. The tensile test results for the material held at various temperatures to establish whether or not either solution heat treatment or aging will occur during forming at these temperatures, are shown in figure 17. The results indicated that the as-received material will not show a solution heat treat response when it is air cooled from temperatures of 950 degrees through 1200 degrees F, nor will an aging response be obtained on the raw material after exposure within this same temperature range.

j. Thickness and Rockwell tests. Thickness and hardness surveys were performed on one inch by 22 inch sample strips furnished with the raw material. The thickness was determined with a micrometer. Rockwell hardness readings were used to obtain the hardness.

The thickness survey results are shown in figure 18. Note that the average thickness of the 0.100 inch nominal material varied from the 0.100 inch to slightly over 0.104 inch, and that the average thickness of the 0.075 inch nominal material varied from about 0.077 inch to 0.079 inch. This variation occurred as a fairly uniform crown in the material. (See figure 19)

The hardness survey readings are shown in figure 20. These readings averaged Rockwell C 36.5. The individual readings did not vary much from this value.

k. Chemical analysis. Hydrogen analyses were run on one sample each from heat numbers 70021 and 70024. Typical microsections were prepared from material taken from two heats of each gauge. These were examined and photomicrographs taken.

The hydrogen analysis results were as follows:

Heat No.	70021	109 ppm.	of hydrogen(average of three runs)
Heat No.	70024	98 ppm.	of hydrogen(average of three runs)

TEST TEMP., °F	HEATING TIME MINUTES	DWELL TIME MINUTES	FINAL BEND ANGLE DEGREES	FINAL BEND RADIUS INCHES	VISUAL APPEARANCE
750	5	5	60	--	CRACKED ALONG FULL LENGTH, OPEN CRACK
850	5	5	102	5/32	FAIRLY LONG CRACK, NOT APPRECIABLY OPEN
950	5	5	103	5/32	VERY SMALL CRACK, APPEARED TO ORIGINATE IN SCRATCHED AREA.
1000	10	5	104	5/32+	FULLY FORMED, NO FAILURE
1000	10	0	99	5/32+	FULLY FORMED, NO FAILURE
1050	10	0	99	5/32+	FULLY FORMED, NO FAILURE
1050	10	0	102	5/32+	FULLY FORMED, NO FAILURE
1075	15	0	102	5/32+	FULLY FORMED, NO FAILURE
1150	10	0	102	5/32+	FULLY FORMED, NO FAILURE

NOTE: THE PLUS SIGN INDICATES THE RADIUS WAS SLIGHTLY (BUT CONSIDERABLY LESS THAN 1/64 INCH) LARGER THAN THE PUNCH RADIUS.

Figure 15. Elevated Temperature Bend Test Results

TEST	STRESS	TEST SECT.WIDTH,IN.AT			% ELONG	
TEMP. °F	K/SQ IN.	END	CENTER	END	IN 2 IN.	REMARKS
950	0	.503	.503	.5035	0.	
950	30	.503	.503	.5035	0.	
950	50	.503	.503	.5035	0.	
950	70	.502	.502	.502	0.5	
950	90	.436	.455	.455	28.5	WELL BEYOND UNIFORM ELONGATION LIMITS
950	0	.503	.5025	.5025		
950	80	.490	.489	.486	6.	LOADED FOR ONE MINUTE (NEAR UNIFORM ELONGATION LIMITS)
950	80	.485	.486	.480	7.5	LOADED FOR TWO MINUTES (NEAR UNIFORM ELONGATION LIMITS)
950	80	.465	.470	.454	20.	LOADED FOR FOUR MINUTES (NEAR UNIFORM ELONGATION LIMITS)
1150	0	.503	.503	.5035	0.	
1150	40	.475	.472	.451	18.	WELL BEYOND UNIFORM ELONGATION LIMITS
1150	0	.503	.503	.502	0.	
1150	35	.485	.483	.476	10.5	SLIGHTLY BEYOND UNIFORM ELONGATION LIMITS.

Figure 16. Uniform Elongation Limit Test Results.

TREATMENT	TENSILE TEST RESULTS		
	YS, K/SQ IN.	TS, K/SQ IN.	%ELONG/2 IN
NONE(CONTROL SAMPLE FOR FIRST EIGHT SAMPLES BELOW)	135	143	15.5
90 MINUTES AT 950° F	135	142	14.5
90 MINUTES AT 950° F + 16 HOURS AT 850° F	135	143	14.5
90 MINUTES AT 1000° F	135	142	15.5
90 MINUTES AT 1000° F + 16 HOURS AT 850° F	134	142	14.5
90 MINUTES AT 1050° F	134	141	15.
90 MINUTES AT 1050° F + 16 HOURS AT 850° F	133	142	15.
90 MINUTES AT 1100° F	134	140	15.
90 MINUTES AT 1100° F + 16 HOURS AT 850° F	134	142	15.
NONE(CONTROL SAMPLE FOR NEXT FIVE SAMPLES BELOW)	146	150	13.
30 MINUTES AT 1200° F	148	150	13.
30 MINUTES AT 1200° F + 16 HOURS AT 850° F	150	151	13.
90 MINUTES AT 1300° F + 16 HOURS AT 850° F	158	162	9.
90 MINUTES AT 1400° F	142	147	10.
90 MINUTES AT 1400° F + 16 HOURS AT 850° F	171	183	2.

Figure 17. Solution Treatment and Aging Response Test Results

LOT NO.		0304	0304	0304	0305	0305	0305	0306	0307	0307	0307	0308	0308	0308	0308
SHEET NO.		1V	2V	3V	1V	2V	3V	1V	1V	2V	3V	1V	2V	3V	4V
LOCATION OF THICKNESS READINGS FROM ONE END	0	.103	.102	.100	.1005	.100	.100	.097	.0775	.078	.079	.0765	.0755	.0755	.076
	2	.100	.1045	.103	.102	.102	.1015	.097	.078	.0785	.080	.077	.076	.077	.0765
	4	.106	.1055	.1045	.1025	.103	.102	.099	.078	.0795	.0805	.0775	.077	.0775	.0775
	6	.106	.106	.105	.1035	.104	.102	.0995	.079	.0795	.081	.078	.077	.078	.078
	8	.1065	.106	.1055	.1035	.1045	.102	.100	.079	.0795	.081	.0785	.0775	.078	.078
	10	.1065	.1065	.106	.104	.105	.1025	.1005	.079	.080	.0815	.078	.0785	.0785	.0785
	12	.1065	.1065	.1055	.1035	.105	.102	.1005	.078	.080	.081	.078	.078	.079	.0775
	14	.1065	.1065	.1055	.1035	.1055	.1025	.1005	.078	.079	.081	.0785	.078	.0785	.0775
	16	.106	.106	.105	.103	.1045	.1045	.0985	.078	.0785	.080	.078	.0765	.078	.0785
	18	.1055	.1055	.1005	.102	.104	.102	.0985	.078	.0795	.078	.078	.0765	.078	.078
	20	.103	.1045	.1025	.0995	.103	.101	.0985	.0775	.0785	.079	.077	.0765	.0775	.078
	22	.102	.1025	.1015	.0965	.101	.0975	.097	.076	.0775	.0785	.077	.0755	.078	.077

AVERAGE OF ABOVE READINGS						
	LOCATION OF THICKNESS READINGS INCHES FROM ONE END					
	2	4	6	8	10	12
FIRST SEVEN SHEETS	.1000	.1016	.1029	.1037	.1042	.1043
SECOND SEVEN SHEETS	.0768	.0776	.0781	.0785	.0787	.0790

Figure 18. Thickness Survey Results

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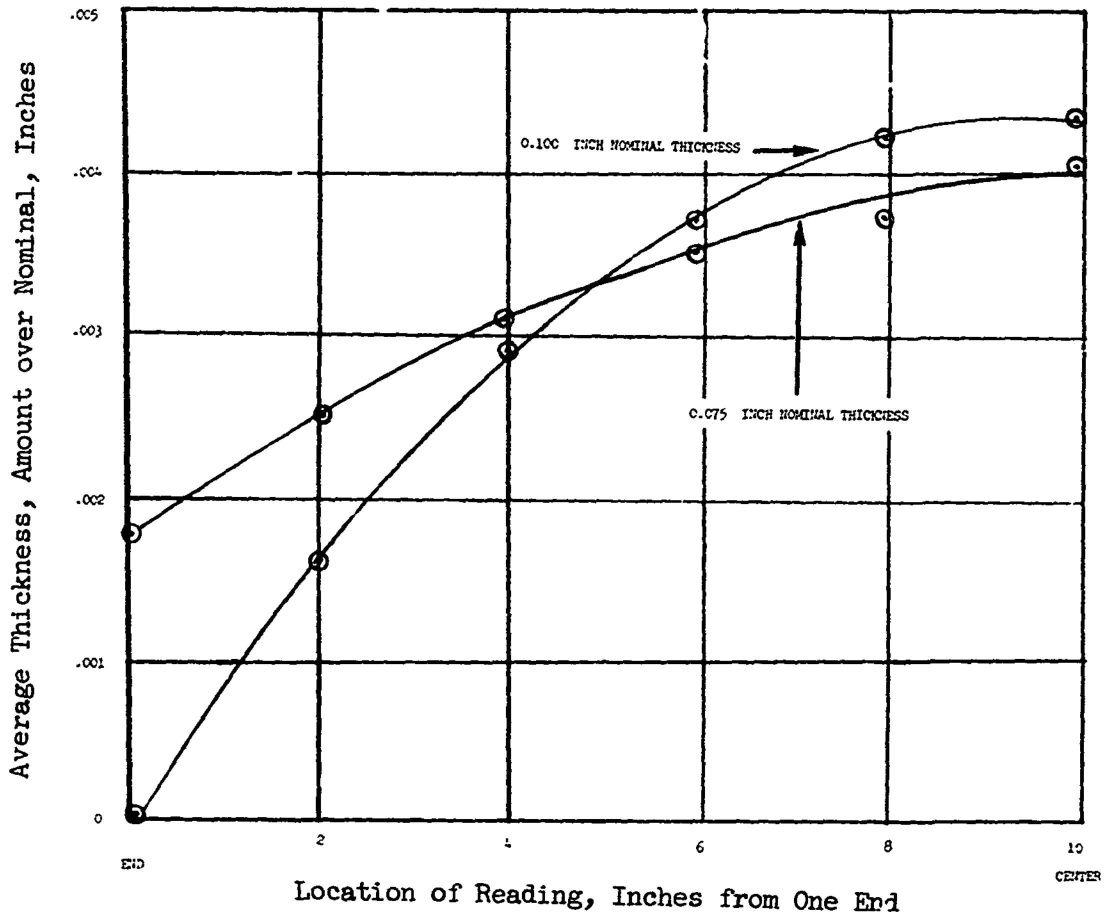

Figure 19. Average Material Thickness Variation

LOT NO.	SHEET NO.	LOCATION OF HARDNESS READING, INCHES FROM ONE END			
		0.5	7.5	14.5	21.5
0304	1V	33.5	35.	35.	35.5
0304	2V	36.	35.5	35.5	36.
0304	3V	37.	36.5	36.	37.
0305	1V	36.5	36.5	36.5	36.
0305	2V	37.	36.5	36.5	36.
0305	3V	35.	35.	35.	35.
0306	1V	36.5	36.5	36.	36.5
0307	1V	35.5	35.5	36.5	36.
0307	2V	36.5	36.	36.5	35.5
0307	3V	37.	36.5	36	36.5
0308	1V	37.5	37.	38.	38.
0308	2V	37.	38.	37.5	38.
0308	3V	37.	37.	37.5	38.
0308	4V	37.5	36.5	37.	38.

Figure 20. Rockwell C Hardness Readings

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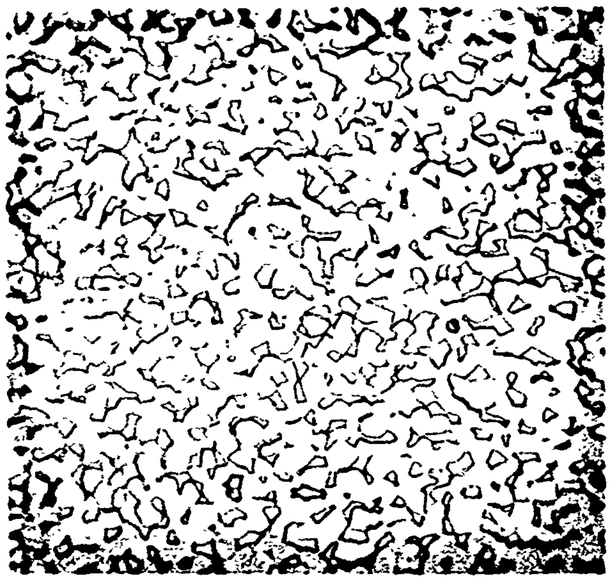
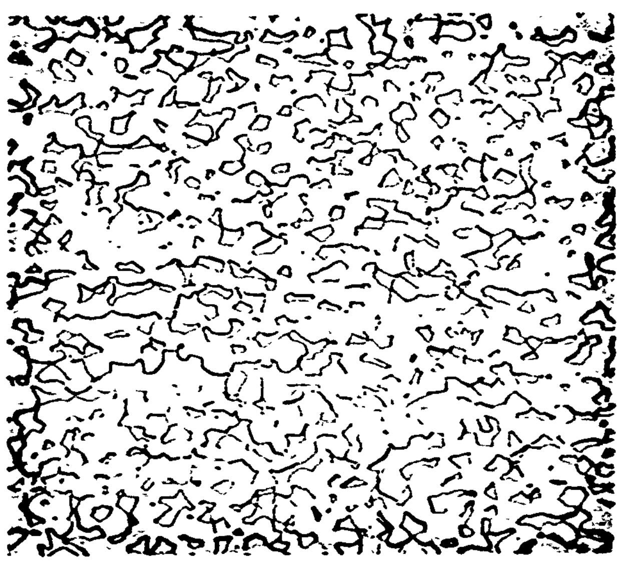
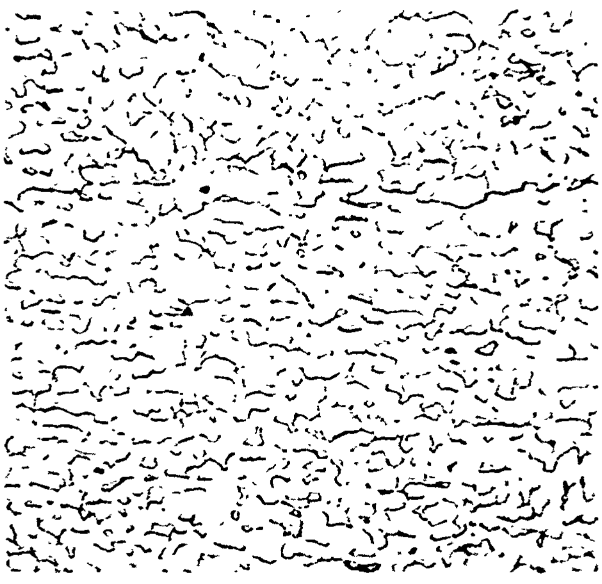


UNFORMED MATERIAL FROM HEAT #70021

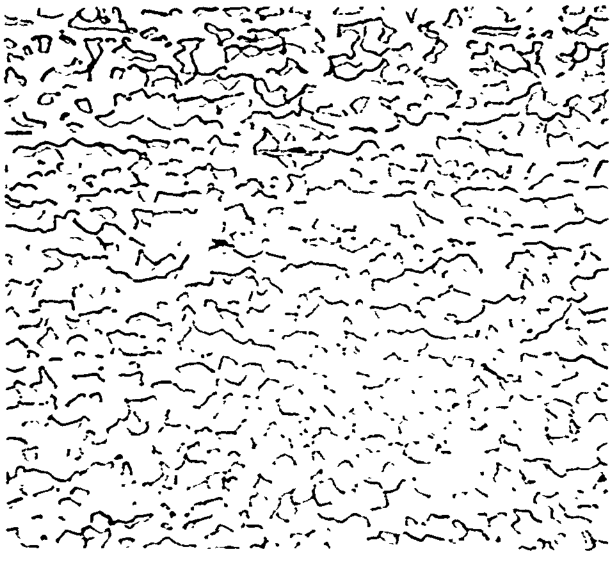


MATERIAL FROM HELMET APPROXIMATELY 70 % FORMED
REFER TO TEST #631B

Figure 21. Photomicrographs of material - Heat #70021

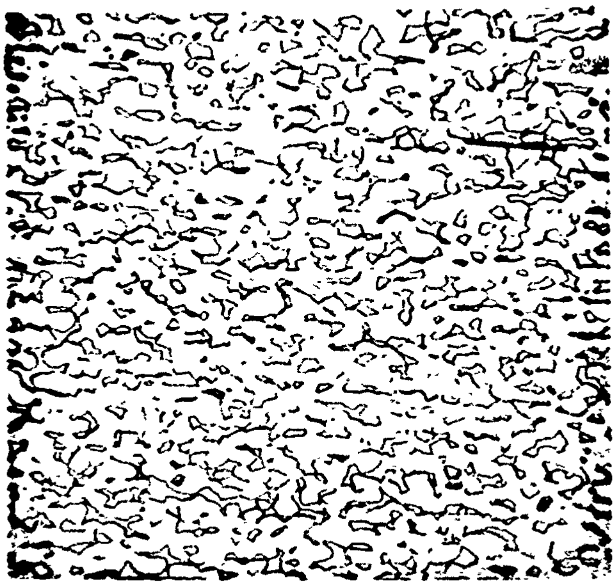


UNFORMED MATERIAL FROM HEAT #70022

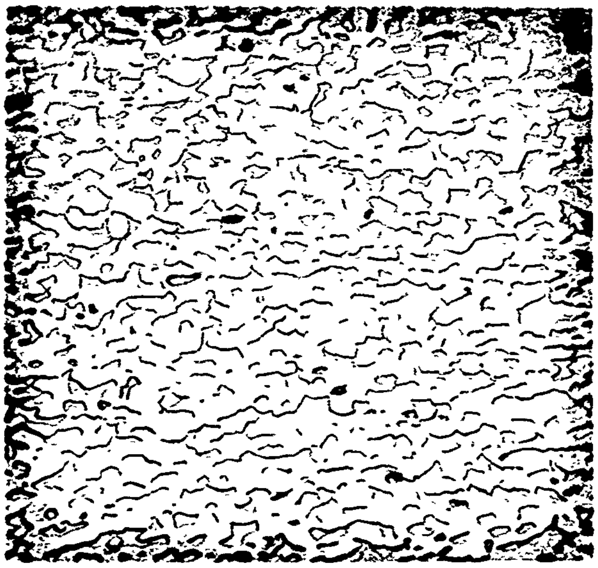


MATERIAL FROM HELMET APPROXIMATELY 40 % FORMED
REFER TO TEST #622E

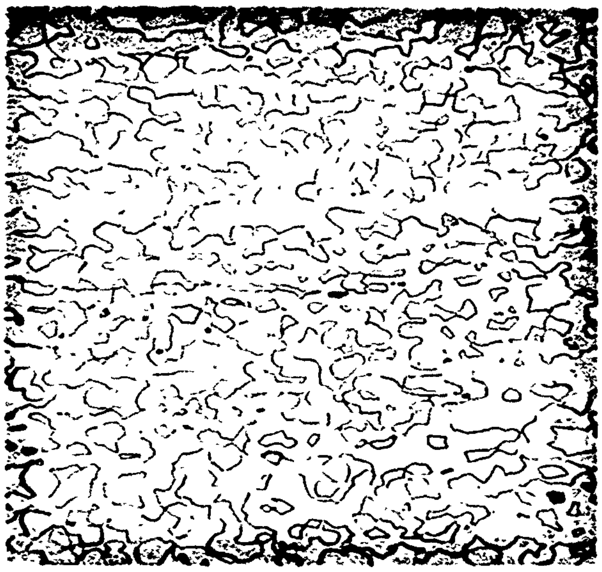
Figure 22. Photomicrographs of Material - Heat #70022



UNFORMED MATERIAL FROM HEAT #70023

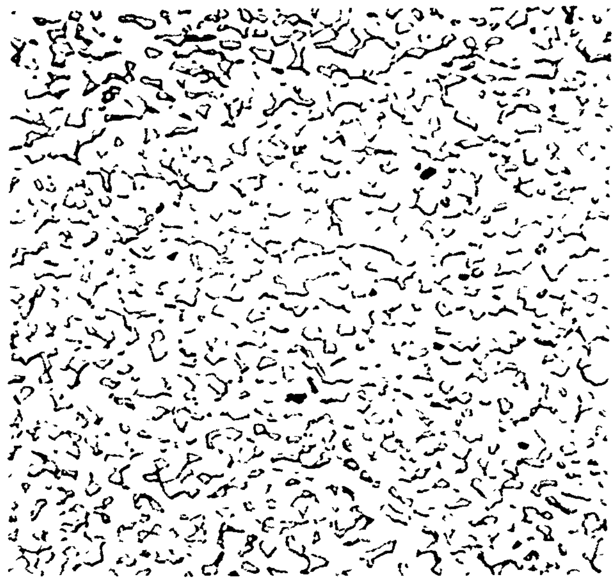


MATERIAL FROM HELMET APPROXIMATELY 60% FORMED - REFER TO TEST #649

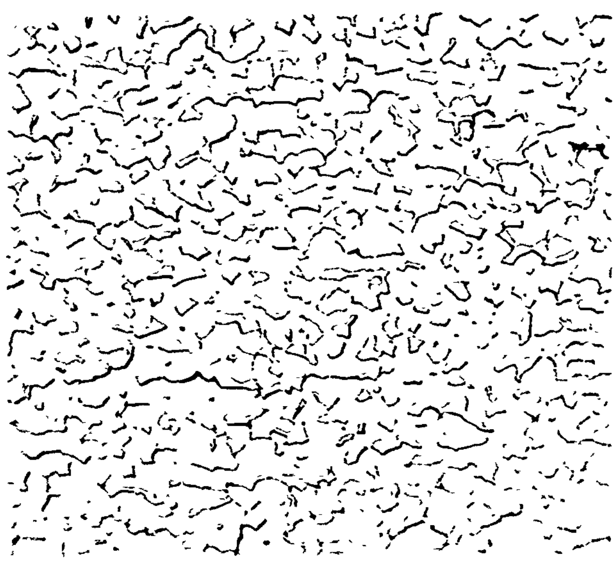


MATERIAL FROM HELMET APPROXIMATELY 40% FORMED - REFER TO TEST #649A

Figure 23. Photomicrographs of Material - Heat #70023



UNFORMED MATERIAL FROM HEAT #70024



MATERIAL FROM HELMET APPROXIMATELY 50% FORMED
REFER TO TEST #623B

Figure 24. Photomicrographs of Material - Heat #70024

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SECTION IV TEST PROCEDURE

TEST PROCEDURE OUTLINE. The procedure developed for explosive forming of Titanium helmets was the result of considerable study and experimentation. A typical planning outline consists of the following:

a. Set temperature control units to pre-determined temperature.
b. Titanium chem-mill to remove surface embrittlement.
c. Apply lubricant to blank and position in die.
d. Apply pre-determined jack pressure.
e. Allow part to soak to forming temperature.
f. Add limited amount of sand to chimney to retain heat.
g. Pull vacuum between part and die (a minimum of 29.2 inches of mercury).
h. Remove excess hot sand (to level of helmet brim)
i. Position previously prepared explosive.
j. Fill chimney with sand
k. Position and clamp sand hopper to top of die.
l. Check vacuum and jack pressure.
m. Fire explosive charge.
n. Remove sand hopper and inspect.
o. Record technical data and results.
p. Repeat the preceding steps as required to complete part in first stage die.
q. Titanium chem-mill to remove surface embrittlement.
r. Trim flange as required to reduce friction.
s. Record thickness readings.
t. Continue forming in second stage die, recording technical data and results.
u. Scribe and trim completed helmet using apply-type tool.
v. Titanium chem-mill to remove surface embrittlement.
w. Take and record thickness and hardness of finished part.
x. Inspect and identify.

SUMMARY OF SUCCESSFUL TESTS. Figure 25 is a history of the first successfully formed helmet (test number 631). This test required 28 separate explosive shots to arrive at an explosive forming technique.

After the helmet formed in test number 631 had been inspected and identified, it was hand-carried by Mr. Jim Orr, Ryan Coordinator to Natick, Mass. and delivered to Helen Agen, Representative of U.S. Army, Quartermaster Research and Engineering Command, (refer to Ryan Shipper 21179). Thickness and hardness readings were taken at Natick, Mass. and the helmet was retained there. With the experience gained in test 631, the number of shots required for later tests was reduced to ten. The final technique, which produced five successful helmets (tests 622C, 622D, 631D, 631E, and 651) is shown in figure 30. A summary of technical data on these tests is given in figure 31. The completed helmets are shown in figure 32.

BLANK MATERIAL;	HEAT XT-70021	BLANK SIZE:	0.100 X 17.5 X 18.5 INCHES
DIE TEMPERATURE:	1200° F	PART TEMPERATURE:	950° F
JACK PRESSURE:	7 TONS EACH JACK	VACUUM:	29.5 IN. MERCURY
LUBRICANT:	EVERLUBE T60	EXPLOSIVE:	DUPONT 5066 PISTOL POWDER

SHOT NO.	AMOUNT OF EXPLOSIVE	LOCATION OF EXPLOSIVE	AMOUNT OF FORMING IN INCHES PER SHOT	AMOUNT OF FORMING IN INCHES TOTAL
1.	25 grams	2 IN. above blank	1.25	1.25
2.	40 grams	2 IN. above flange	0.25	1.50
3.	50 grams	2 IN. above flange	0.375	1.875
4.	50 grams	1 IN. above flange	0.25	2.125
5.	50 grams	1 IN. above flange	0.125	2.25 (1)
6.	60 grams	2 IN. above flange	0.25	2.5
7.	60 grams	2 IN. above flange	0.125	2.625
8.	60 grams	2 IN. above flange	NO MOVEMENT	2.625
9.	60 grams	2 IN. above flange	0.125	2.75
10.	60 grams	2 IN. above flange	0.375	3.125
11.	60 grams	2 IN. above flange	0.375	3.5
12.	60 grams	2 IN. above flange	0.25	3.75
13.	50 grams	1 IN. above flange	0.125	3.875
14.	60 grams	2 IN. above flange	0.125	4.0
15.	70 grams	2 IN. above flange	0.125	4.125
16.	60 grams	1 IN. above flange	0.25	4.375
17.	60 grams	1 IN. above flange	0.25	4.625
18.	60 grams	1 IN. above flange	0.125	4.75
19.	60 grams	1 IN. above flange	NO MOVEMENT	4.75
20.	80 grams	1 IN. above flange	0.125	4.875
21.	80 grams	1 IN. above flange	0.3125	5.187(2)
22.	25 grams	2 IN. above flange	0.375	5.562
23.	25 grams	2 IN. above flange	0.0625	5.625
24.	40 grams	1 IN. above flange	0.25	5.875
25.	40 grams	1 IN. above flange	0.0625	5.937
26.	40 grams	1 IN. above flange	NO MOVEMENT	5.937
27.	60 grams	1 IN. above flange	0.0625	6.0
28.	80 grams	1 IN. above flange	0.25	6.25 (3)

(1) (TRIMMED ONE INCH FROM EACH END AND ONE HALF INCH FROM EACH SIDE OF PART TO REDUCE FRICTION AND PERMIT MATERIAL TO FLOW. OBTAINED THICKNESS READINGS AND HARDNESS READINGS (SEE FIGURE 26). ON FOLLOWING SHOTS USED LUBRICANT COMPOSED OF EQUAL PARTS BY VOLUME OF ELECTRO FILM 22T AND SUPERBRITE 1160 GLASS BEADS; DIE TEMPERATURE VARIED FROM 1170° F to 1270° F)

(2) (AT THE TWENTY-FIRST SHOT, THE VACUUM WAS LOST DUE TO THE FLANGE PULLING INSIDE THE THERMOCORE SEAL RING ON THE DIE. THE FLANGE WAS TRIMMED TO RECTANGULAR SHAPE AND STRIPS OF 75A TITANIUM, 0.080 INCHES THICK AND 1.5 INCHES WIDE WERE WELDED ON (SEE FIGURE 27), AND THE FOLLOWING READINGS TAKEN:

FLANGE THICKNESS (FOUR PLACES): 0.113 0.116 0.116 0.112
THICKNESS AT CENTER OF CROWN: 0.075
ROCKWELL HARDNESS (FOUR PLACES): A67 A67 A67 A67.5

THE PART HAVING BEEN FORMED TO WITHIN 3/16 INCHES OF THE BOTTOM OF THE FIRST STAGE DIE= THE TEST WAS CONTINUED, USING THE SAME TECHNIQUES, BUT IN THE SECOND STAGE DIE AND WITH EVERLUBE T60 FOR LUBRICANT. THE DIE TEMPERATURE AVERAGED 1210° F FOR THE REMAINDER OF THE TEST).

(3) (THE HELMET WAS CONSIDERED FULLY FORMED (SEE FIGURE 28); THE HELMET WAS TRIMMED AND THEN CLEANED USING A PICKLING PROCESS (SEE FIGURE 29).

Figure 25. History of Test Number 631

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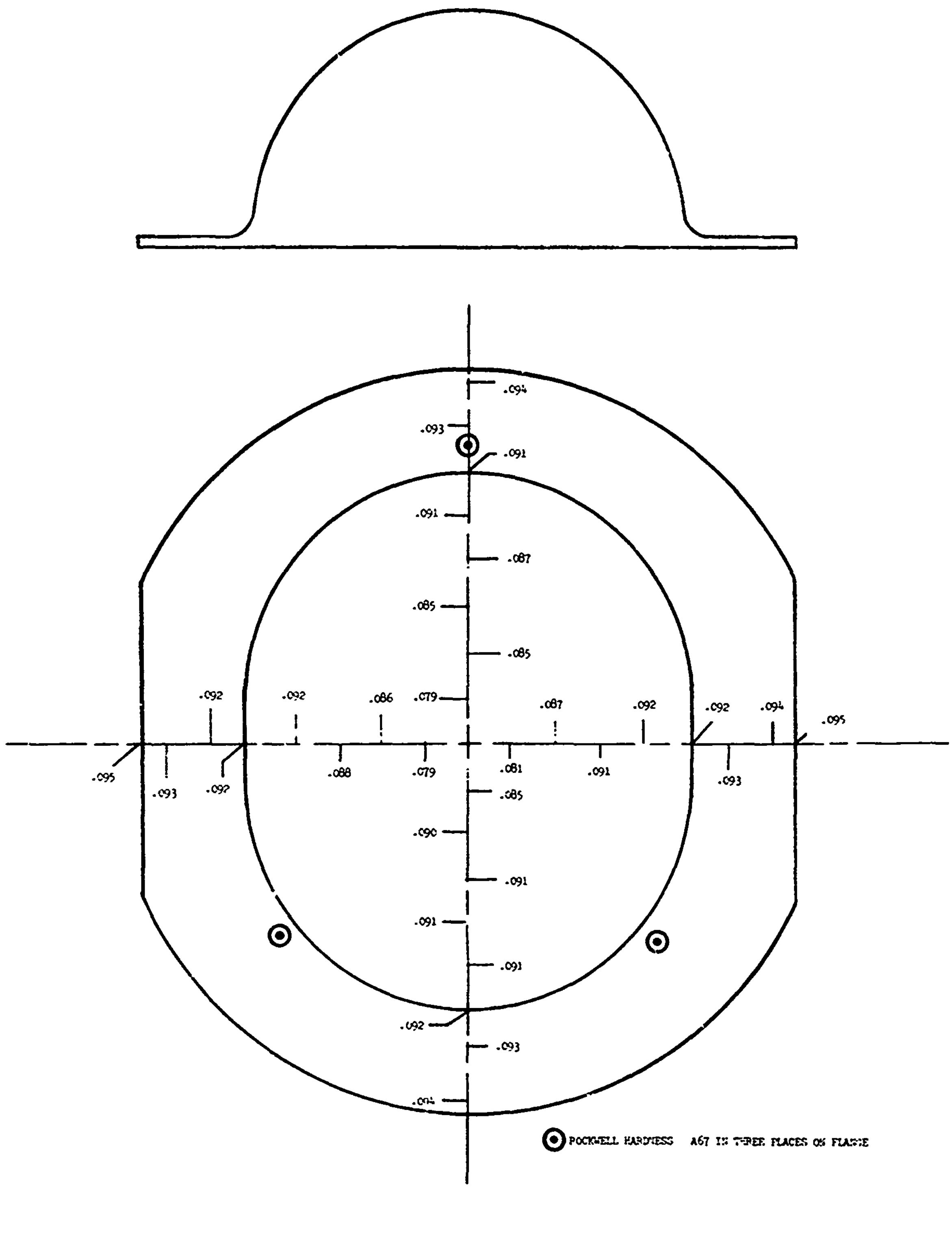


Figure 26. Thickness and Hardness - Test 631, First Stage

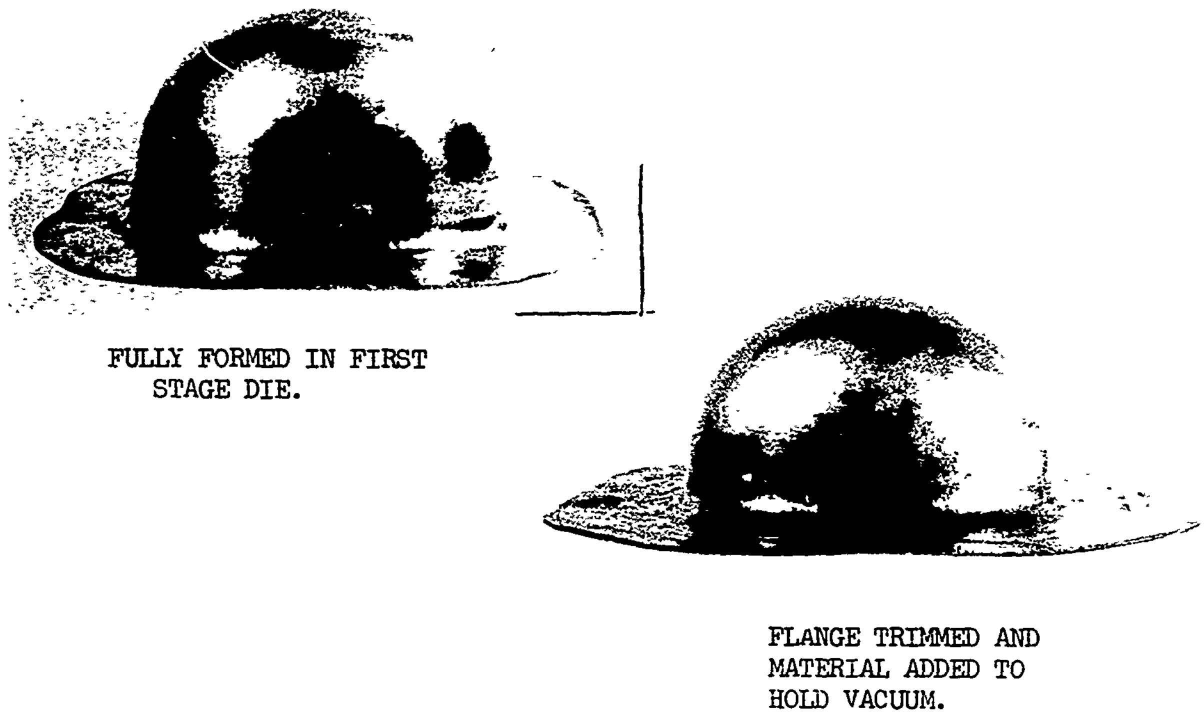
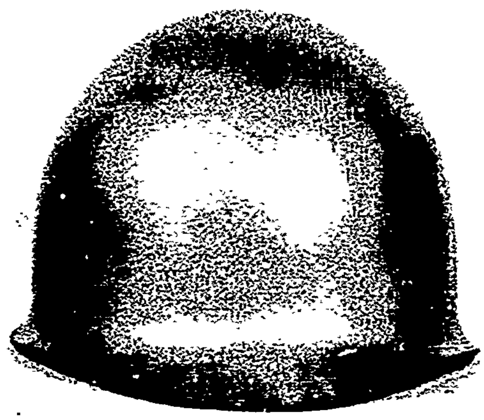
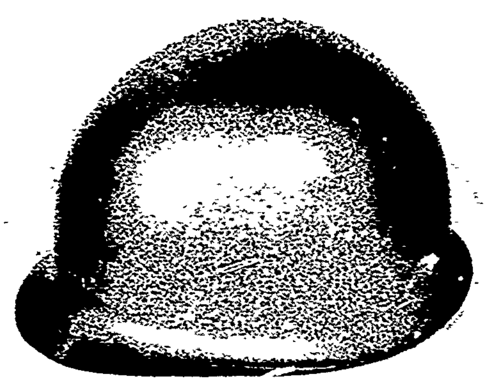


Figure 27. Helmet at End of First Stage Forming

Figure 28. Helmet at End of Second Stage Forming



FRONT VIEW



SIDE VIEW

Figure 29. Helmet Formed in Test 631 After Cleaning and Trimming.

MATERIAL AND DIE CONDITIONS			
BLANK SIZE:	22 X 22 INCHES TRIMMED TO 18 X 19 INCHES.		
DIE TEMPERATURE:	1250° F	PART TEMPERATURE:	1200 to 1250° F
JACK PRESSURE:	5 TO 8 TONS EACH JACK	VACUUM:	29.5 IN. MERCURY
LUBRICANT:	EVERLUBE T60	EXPLOSIVE:	DUPONT 5066 PISTOL POWDER

PROCEDURAL STEPS:

A. TRIM AND DEBURR BLANK.
B. CHEM-MILL BLANK TO REMOVE SURFACE EMBRITTLEMENT (SEE NOTE 1).
C. POSITION PRE-LUBRICATED AND PRE-HEATED BLANK IN FIRST STAGE DIE.
D. FORM IN FIRST STAGE DIE (FIRST FIVE SHOTS).
E. REMOVE PART FROM DIE, CHECK THICKNESS AND HARDNESS.
F. CHECK FOR FLANGE EXCESS, TRIM AND DEBURR AS REQUIRED TO REDUCE FRICTION.
G. CLEAN TO REMOVE SCALE (SEE NOTE 2).
H. CHEM-MILL OR ETCH TO REMOVE SURFACE EMBRITTLEMENT (SEE NOTE 1).
I. INSPECT FOR CRACKS.
J. LUBRICATE PART AND POSITION IN SECOND STAGE DIE.
K. FORM IN SECOND STAGE DIE (SEE SHOTS 6 THROUGH 10).
L. REMOVE PART FROM SECOND STAGE DIE.
M. CHECK PART USING APPLY-TYPE TOOL AND SCRIBE TRIM LINE.
N. TRIM AND DEBURR.
O. CLEAN TO REMOVE SCALE (SEE NOTE 2).
P. CHEM-MILL (SEE NOTE 1).
Q. CHECK THICKNESS AND HARDNESS (SEE FIGURE 31).
R. ZYGLO INSPECT FOR CRACKS.

SUMMARY OF SHOTS.

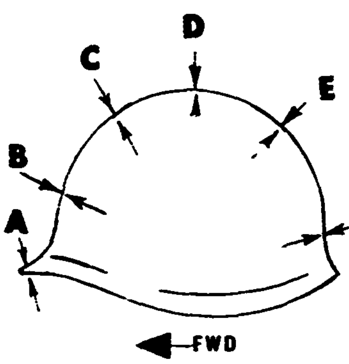
SHOT NO.	AMOUNT OF EXPLOSIVE IN GRAMS	LOCATION OF CHARGE	DIE
1.	60	CENTER OF PART, AT BRIM LEVEL	1st STAGE
2.	70	CENTER OF PART, AT BRIM LEVEL	1st STAGE
3.	80	CENTER OF PART, AT BRIM LEVEL	1st STAGE
4.	85	CENTER OF PART, AT BRIM LEVEL	1st STAGE
5.	90	CENTER OF PART, 3 IN. BELOW BRIM LEVEL	1st STAGE
6.	70	CENTER OF PART, AT BRIM LEVEL	2nd STAGE
7.	75	CENTER OF PART, AT BRIM LEVEL	2nd STAGE
8.	80	CENTER OF PART, AT BRIM LEVEL	2nd STAGE
9.	90	CENTER OF PART, AT BRIM LEVEL	2nd STAGE
10.	90	CENTER OF PART, 3 IN. BELOW BRIM LEVEL	2nd STAGE

NOTES:

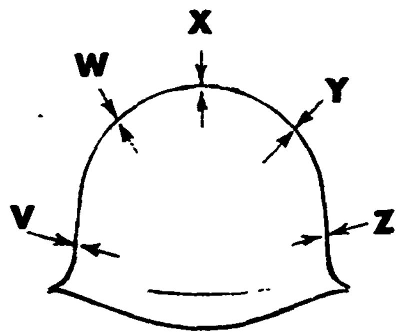
1. CHEM-MILL IN HYDROFLOURIC ACID, CHROMIC ACID AND WETTING AGENT SOLUTION AT 115° F.
2. CLEAN IN NITRIC-HYDROFLOURIC SOLUTION AT AMBIENT TEMPERATURE.

Figure 30. Technique Developed For Forming Helmets

TEST NO.		622C	622D	631	631D	631E	651
SERIAL NO.		1	2		2	3	2
HEAT NO.		XT-7022	XT-7022	XT-7021	XT-70021	XT-70021	XT-70023
GAGE		0.075	0.075	0.100	.100	0.100	0.100
THICKNESS READINGS AT LOCATIONS INDICATED	A	0.077	0.075	DATA NOT AVAILABLE SEE PARAGRAPH 4.2	0.097	0.090	0.097
	B	0.069	0.063		0.080	0.077	0.086
	C	0.072	0.065		0.081	0.083	0.090
	D	0.064	0.057		0.071	0.071	0.071
	E	0.070	0.062		0.087	0.079	0.072
	F	0.071	0.064		0.080	0.079	0.081
	V	0.076	0.065		0.082	0.081	0.090
	W	0.071	0.064		0.081	0.082	0.084
	X	0.064	0.057		0.071	0.071	0.071
	Y	0.063	0.063		0.083	0.082	0.083
	Z	0.074	0.085		0.086	0.082	0.090
HARDNESS		C43	C43		C36.5	C37	C39.5
NET WEIGHT		2 LB. 6.5 OZ.	1 LB.14.50 OZ.		2 LB. 6.5 OZ.	2 LB. 6.5 OZ.	2 LB. 7 OZ.

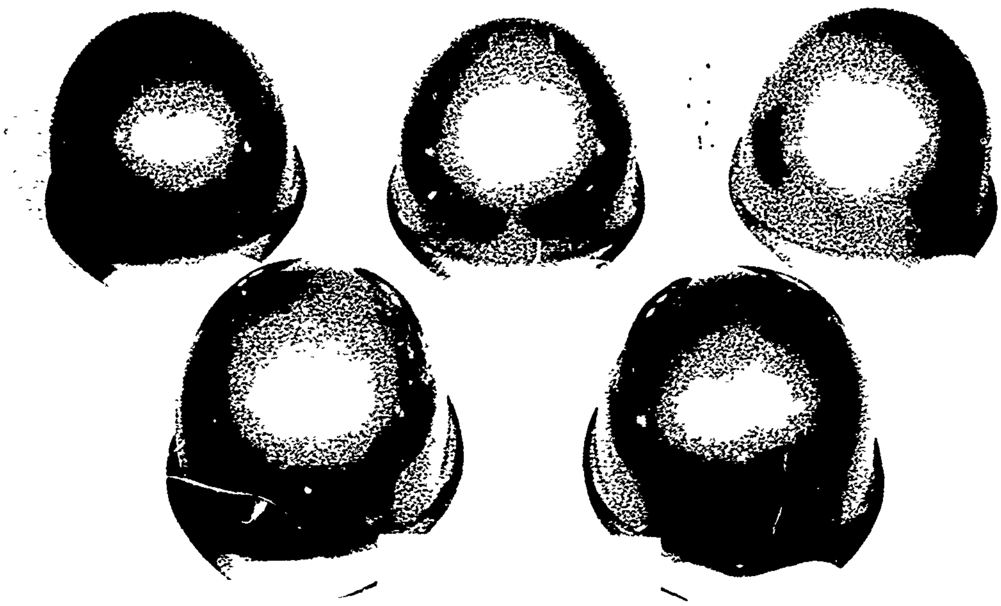


SIDE VIEW CROSS SECTION



FRONT VIEW CROSS SECTION

Figure 31. Thickness and Hardness Survey of Completed Helmets



Group of completed helmets.
Covering is a vinyl protective coating.

Figure 32. Group of Completed Helmets

SECTION V SUMMARY

5.1 SUMMARY OF UNSUCCESSFUL TESTS. In the process of arriving at a successful explosive forming technique, a series of helmets were damaged. The damage, generally, fell into three categories: (a) excessive wrinkles, (b) metal strain marks or (c) fractures. Excessive wrinkling occurred in tests numbered 622A, 622B, 649A, and 623C. (See figures 33, 34, and 35.) The wrinkles were caused by insufficient hydraulic jack pressure. The extent of the wrinkling was so great that no effort was made to flatten the material and continue the tests. Strain marks and evidence of metal fatigue appeared in the inside crown of the helmets in tests 631C and 631F (see figure 36). It is believed this was caused by work hardening of the material resulting in surface embrittlement or by excessive hydraulic jack pressure. Chem-milling was used to prevent surface embrittlement. Adjustment of jack pressure to that required to prevent the material being drawn too rapidly into the die corrected both wrinkling and strain marks. The fractures shown in figures 34, 35, 36, and 37 occurred in tests 623, 623A, 623B, 631A, 631B, 649, 649B, and 651. The cause of the fractures is, probably excessive jack pressure, metal fatigue or a combination of the two. Figure 38 contains a summary of incomplete helmets which failed in forming.

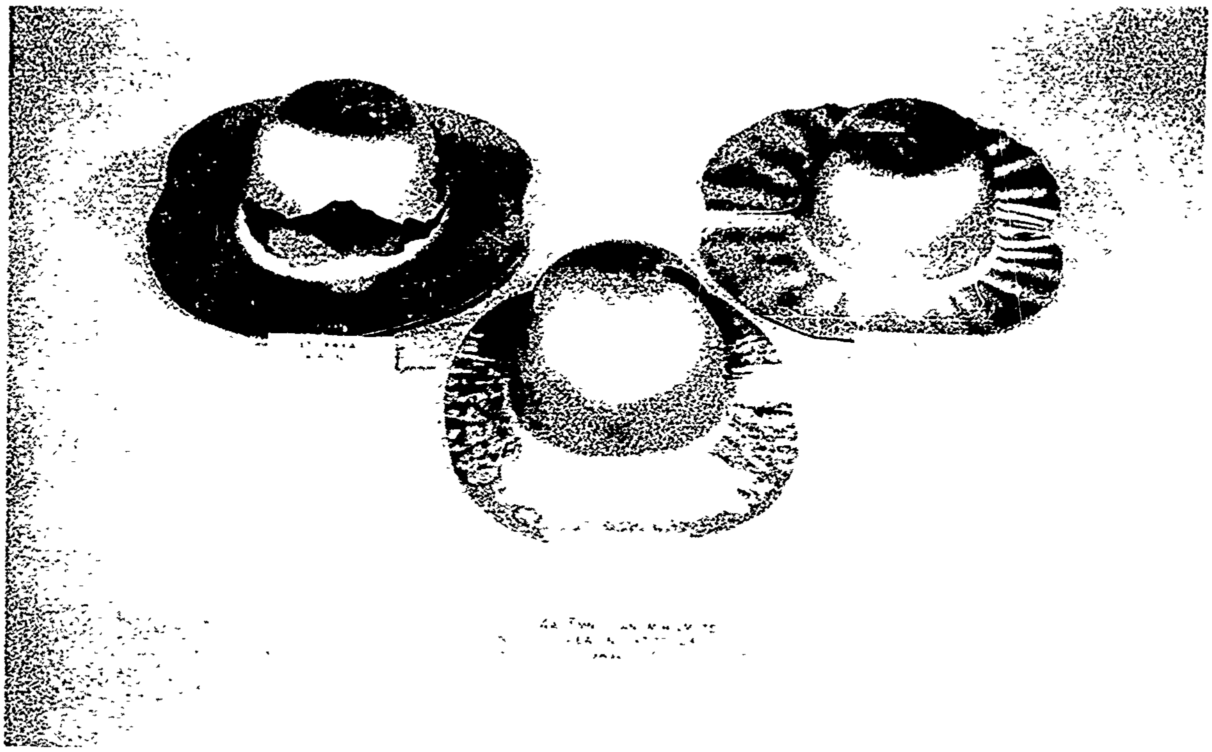
NOTE

Sections of test parts 623 and 623A were used for etch and bend test results.

5.2 SUMMARY ON SHIPPABLE HELMETS. Subject contract states that a total of (10) shaped helmet samples are to be furnished in the annealed condition, and (4) to be furnished in the as-formed condition. Inasmuch as the helmets were formed at temperatures of 1200 degrees F to 1250 degrees F, it was felt that all shippable helmets fall within the annealed as well as the as-formed condition. Because of incomplete helmets falling in various sizes and shapes, it was felt that a somewhat accurate trim could not be made without the benefit of additional apply-type scribe and trim tools to fit the various sizes and shapes. Rather than make the additional tooling, flanges or brims were left untrimmed on the incomplete helmets. All completed helmets are identified on the inside of the visor. Incomplete helmets are identified with paper sticker on inside of helmet.

Hardness survey and section thickness surveys were made and recorded on completed helmets. Surveys were not made on incomplete helmets. Completed helmets were sprayed with vinyl protective coating to prevent marring during handling and shipping.

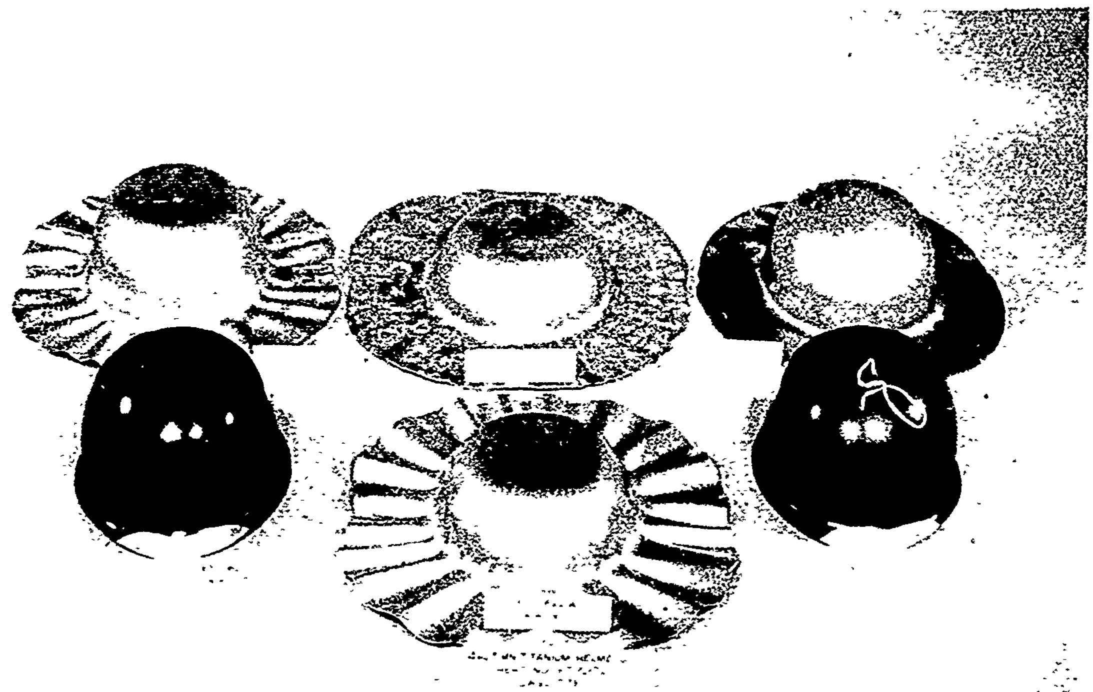
Zyglo inspection of individual completed helmets showed no signs of cracks. Indications that did show up, appeared as surface scratches and nicks when viewed through a six-power microscope.



Test No. 649 and 649A shows fractured helmets caused by work hardening of material and/or excessive clamping pressure in die. Test No. 649B. Pronounced wrinkles caused by insufficient clamping pressure.

61B073

Figure 34. Tests 649, 649A & 649B

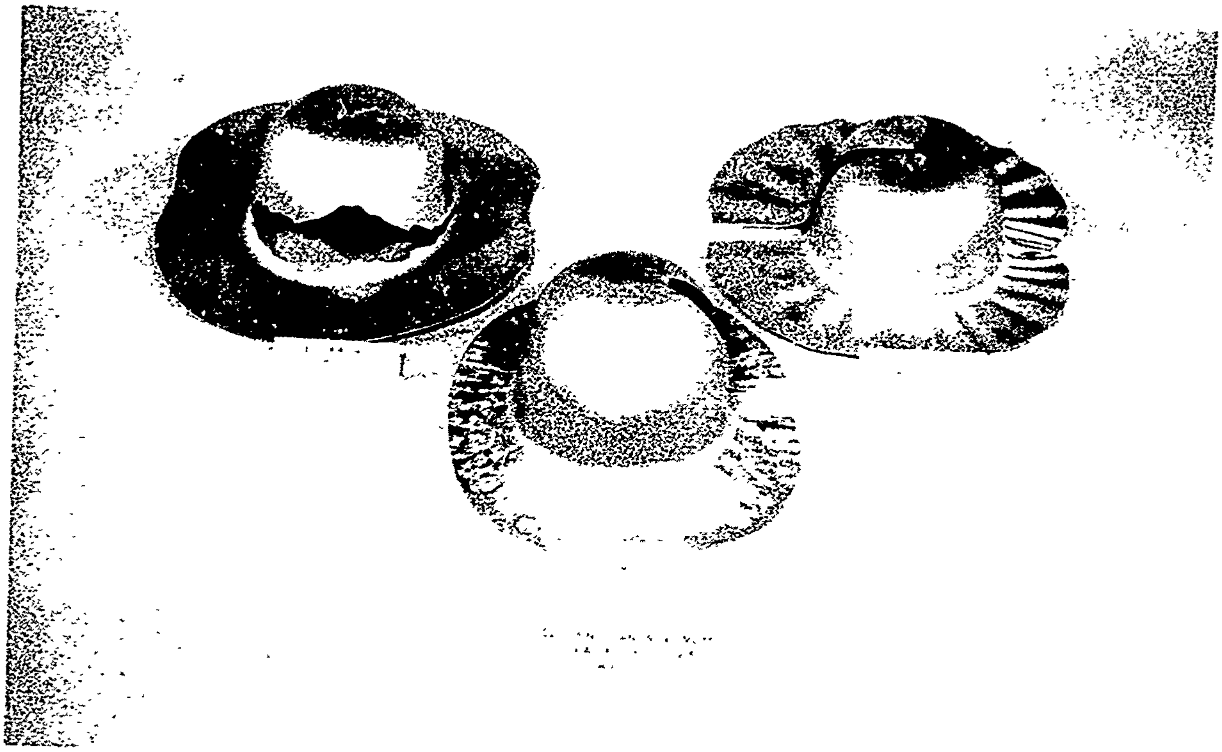


1. Test No. 622A and 622B - Pronounced wrinkles caused by insufficient clamping pressure in die.

2. Test No. 622C and 622D - Helmets formed and trimmed complete. Sprayed with protective coating.

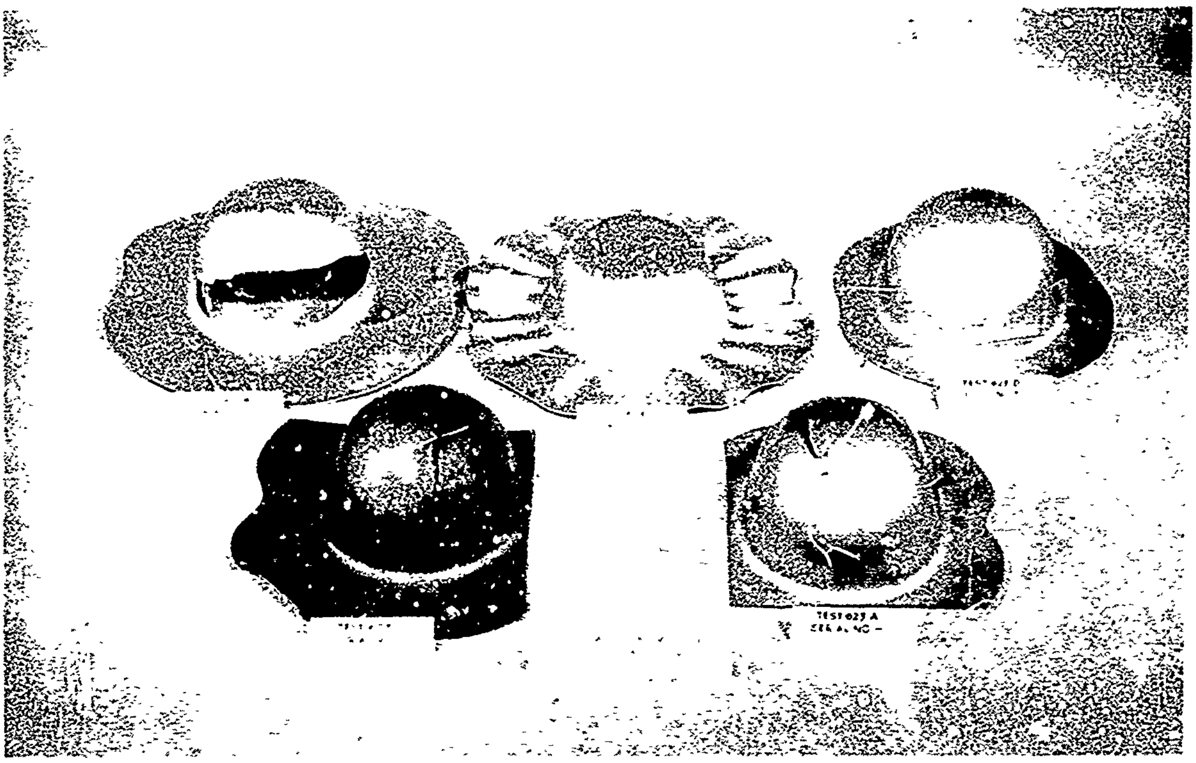
3. Test No. 622E and 622F - Wrinkles caused by insufficient clamping pressure. In process of trying to remove wrinkles, helmets were damaged.

Figure 33. Tests 622A, 622B, 622C, 622D, 622E, 622F



Test No. 649 and 649A shows fractured helmets caused by work hardening of material and/or excessive clamping pressure in die. Test No. 649B. Pronounced wrinkles caused by insufficient clamping pressure.

Figure 34. Tests 649, 649A & 649B

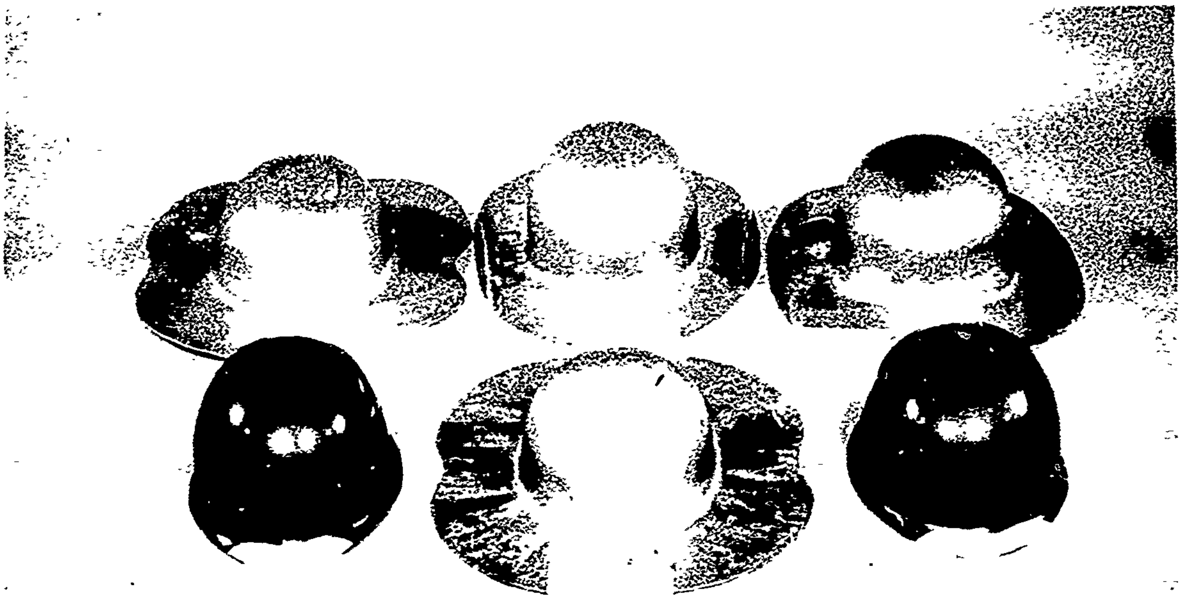


1. Test No. 623, 623A and 623B - Fractures caused by material work hardening and/or excessive clamping pressure.

2. Test No. 623C - Excessive pronounced wrinkles caused by insufficient clamping pressure.

3. Test No. 623D - Partially formed helmet formed by differential process. See writter report for details.

Figure 35. Tests 623, 623A, 623B, 623C, 623D



1. Test No. 631A and 631B - Fractures because of material work hardening and/or too great a clamp pressure.

2. Test No. 631C and 631F - Shows metal fatigue on inside crown caused by material work hardening.

3. Test No. 631D and 631E - Formed and trimmed complete and sprayed with protective coating.

Figure 36. Tests 631A, 631B, 631C, 631F, 631D, 631E

1. Test No. 651 - Formed and trimmed helmet complete and sprayed with protective coating.

2. Test No. 651A - Fracture caused by material work hardening and/or too great a clamping pressure.

Figure 37. Tests 651, 651A

TEST NO.	SERIAL NO.	GAGE	MATERIAL	HEAT NO.	QTY SHIPPED	NOTES 1	2	3	4	5	6
622A	5	0.075	4Al-3Mn TITANIUM		1	X					
622B	3	0.075			1	X					
622E	4	0.075			1	X	X				X
622F		0.075			1	X	X				
623		0.075		XT-70023	1			X			X
623A		0.075			1			X			X
623B	3	0.100			1			X			X
623C	2	0.100			1	X					
623D	1	0.100	4Al-3Mn TITANIUM		1					X	
631A	6	0.100			1			X			
631B	5	0.100			1			X			X
631C	1	0.100		XT-70021	1				X		
631F	4	0.100			1				X		
649	3	0.075			1			X			X
649A	2	0.075			1	X					X
649B	3	0.075		XT-70023	1			X			
651A	1	0.100	4Al-3Mn TITANIUM		1			X			

NOTES:
1. EXCESSIVE WRINKLING DUE TO INSUFFICIENT HYDRAULIC JACK PRESSURE.
2. DAMAGED BY HEAT AND HAMMER PEEN MARKS WHILE REMOVING WRINKLES.
3. FRACTURED DUE TO EXCESSIVE HYDRAULIC JACK PRESSURE AND METAL FATIGUE.
4. METAL STRAIN MARKS APPEARED INSIDE OF CROWN.
5. DIFFERENTIALLY FORMED HELMET (SEE PARAGRAPH 8.2)
6. PORTIONS OF PART USED FOR LABORATORY TESTS.

Figure 38. Summary of Parts That Failed in Forming.

SECTION VI REPORTS

6.1 REPORTS REQUIRED. The Statement of Work directed the contractor to submit monthly reports which should include the following:

Technical progress and future plans.
An estimate of the percentage of work completed to date.
An estimate of the percentage of estimated costs incurred to date.
A statement as to sufficiency of unexpended funds.

The Statement of Work also required 30 copies of a Final Report, a complete set of photographs of each step of the development process and a set of 3-1/4 by 4 inch color glass slides with a bridf description with each slide.

6.2 REPORTS SUBMITTED. Monthly reports were submitted as directed from January 1960 through May 1961, with the exception of the report for July 1960. This, the final report, also serves as the report for June 1961. As part of this report, but under separate cover, is a set of color glass slides showing the explosive forming process, improvements in equipments, and results of the tests, with a 3 by 5 inch card describing each slide.

6.3 SUMMARY OF PROGRESS REPORTS. The following is a synopsis of the progress reports submitted:

January, 1960
- Contract received
- Work started on helmet master model
- Contractor directed not to order complex titanium at this time.

February, 1960
- Awaiting contract revision pertaining to material
- Continued work on helmet master model
- Contractor continued own research into explosive forming at elevated temperatures
- Experiments proved titanium blanks can be heated to temperatures in excess of 1000 degrees F by using Cal-rods to heat the die.

March, 1960
- Material on order
- Republic Steel advised that they would not guarantee to meet physical requirements of the material specification, but would make material on "best effort" basis.
- Contractors research into explosive forming of titanium to a 6 inch hemisphere proved satisfactory. The hemispheres were formed at a temperature of approximately 1000 degrees F. A thickness survey indicated the variation to be 0.004 inches.
- Work started on first and final stage dies.

April, 1960
- Titanium material promised for 10 July, 1960
- Dies expected to be complete in latter part of June 1960.
- Received Cal-rod heating elements oor heating dies.

May, 1960
- Dies about 90 percent complete.

June, 1960
- Titanium delivery promised for 30 July, 1960. Delay due to furnace breakdown at Republic Steel

Dies complete. Performed experiments on dies with other materials. Photos of dies taken.

August, 1960

Material not received. New date of delivery of September promised.
Continued experiments. Helmet-like shape were produced using pure titanium
Actual progress on contract stopped pending receipt of material.
Approximately 40 percent of the task assigned completed.

September, 1960

Material received 1 September, 1960.
Preliminary tests of complex titanium indicates much more pressure required for forming compared to commercially pure titanium. A Sand Hopper, to contain additional sand required because of the increased pressures, has been designed, and copy of the design forwarded with this report.
Also, forwarded metallurgical report on specimen of Manganese complex Titanium.
58 percent of the task assigned has been completed.
A 90 day extension of contract was requested due to late receipt of material.
Forwarded with this report were: 11 copies each of the following:

- Ryan photos numbered 60693, 60698, 60699, 60700
- Purchase order 41405 for material from Republic Steel
- Raw material evaluation
- Ryan Drawing 120X-37-SE (2 sheets)

October, 1960

Fabrication of Sand Hopper complete
Sand Hopper tested and perfected

November, 1960

Explosive forming operations started
Developed a lubricant to overcome material resistance to die
Found that a Chem-mil operation was required to remove surface embrittlement of titanium.

December, 1960

Die must be reworked to revise clamping of cal-rods to die. Method of clamping must allow for heat expansion or cal-rods burn off at junctions.
Forwarded photos of formed helmet.
Forwarded material thickness readings for formed helmet. Material thinning 0.025 inches. A new technique is to be tried to reduce thinning.

January, 1961

Most of the month used to rework die and revise cal-rod clamping. No parts were made.

February, 1961

Twelve helmets formed through first stage
Four of the twelve helmets formed through second stage
Forwarded thickness readings on formed parts.

March, 1961

Six helmets formed through first stage.
One helmet formed and ready for trimming using 0.100 inch material
Material thinning at crown of helmet is 0.010 inch.
Some delay in program due to burning out three cal-rod units

April, 1961

Replaced burned out cal-rod units.
Other work suspended awaiting allocation of funds.

May, 1961

Explosive forming completed.

Six helmets formed, trimmed, cleaned and identified.

One helmet delivered

Seventeen helmets formed to various stages but not completed due to excessive wrinkles, fractures and metal fatigue.

One helmet formed by differential forming method.

SECTION VII DIFFERENTIAL FORMING

7.1 DIFFERENTIAL FORMING. An attempt was made to form a helmet by other than explosive forming. One helmet was formed approximately 85 percent using this method, but could not be completed due to lack of tooling. The step by step procedure was as follows:

> The existing first stage die was jury-rigged in an HPM hydraulic press for use with cold punch.
> A blank of 0.100 inch 4Al-3Mn Titanium, Heat no. XT-70024 was chem-milled to remove surface embrittlement.
> Die temperature 1250 degrees F. Die pad pressure about 20 tons.
> Blank was permitted to soak to about 800 degrees F.
> One cycle of press f rmed helmet 85 percent in first stage die.
> Helmet was cleaned b[illegible].
> Thickness survey on helmet showed maximum thinning of 0.009 inch. A variation of 0.094 inch to 0.100 inch in localized area just above helmet brim was caused by mis-alignment in jury-rigged punch/die setup.

The contractor feels that, with a tool specifically designed for a press with punch and die control, plus regulated ring pressure, the thinning condition can be improved and satisfactory helmets produced using this Differential-Forming Process. A photo of the partially formed helmet is provided in figure 35 , test number 623D, serial number 1.

See differential helmet sample for thickness survey.

SECTION VIII CONCLUSIONS AND RECOMMENDATIONS

8.1 CONCLUSIONS. The work accomplished on this project indicates that it is possible to form helmet like shapes from manganese complex titanium alloy using explosive forming.

The disadvantages of explosive forming are:

- Extremely slow production rate.
- Variation in thickness is considerably greater than desirable for maximum ballistic protection.
- Elevated temperature must be used to eliminate cracking and thinning and reduce spring back.

At the present stage of development, the slow and costly process of explosive forming appears impractical as a means of mass-production of helmets. As described in the technical portion of this report, several shots, with the time required for positioning, charging and cleaning, are required to form the part without splitting or wrinkling.

Although not within the scope of this contract, a preform was made using the differential forming technique. Even under the adverse conditions of a jury-rig setup, the part was formed with a minimum amount of thinning and without wrinkles.

8.2 RECOMMENDATIONS. It is recommended that the explosive forming technique be considered as a final sizing technique after preforming by the differential forming method. Explosive sizing would accomplish the finish form of visor and brim area, which is difficult to form by the heavy press method.

Because of the speed and cleanliness of the differential forming method, a partially formed helmet could probably be produced on a single press at a rate of one or two per minute. The helmet would then be final formed using the explosive gas technique.

Figure 39 is an illustration which demonstrates a production technique to mass produce titanium helmet like shapes. Titanium dies would be cut to size and fed to the machine. The machine would preheat the die in a furnace and position it in the first die. A heavy press would do the major part of the forming by the differential temperature forming technique. The part would then be automatically shifted to the next die where the final form would take place at the next troke of the press by exploding gas within the part cavity. The use of gas eliminates the use of sand or other messy forming media which has been a serious delaying factor in helmet production. The helmet shape would, at the next stroke of the press, be moved automatically to the third die which would de-brim the helmet on the next stroke of the press. The part would then be automatically transferred to a conveyor for deburring, cleaning, inspecting and packaging. A completed helmet would be produced with each stroke of the die.

8.3 It is further recommended that additional development work be accomplished to ascertain the amount of preform that can be obtained in the first forming operation, holding thinning to a minimum, the optimum working temperature, and whether water cooling or some other means of cooling the punch is required. The determination of the amount of preform possible will have a bearing on the gas explosive forming phase. The optimum working temperature requires research since experience has shown that if the center of the blank is heated above 800 degrees F it will thin excessively, and the periphery should be about 1200 degrees F. Cooling of the punch by some means is required so that contact will cause cooling of the center of the blank to prevent excessive thinning.

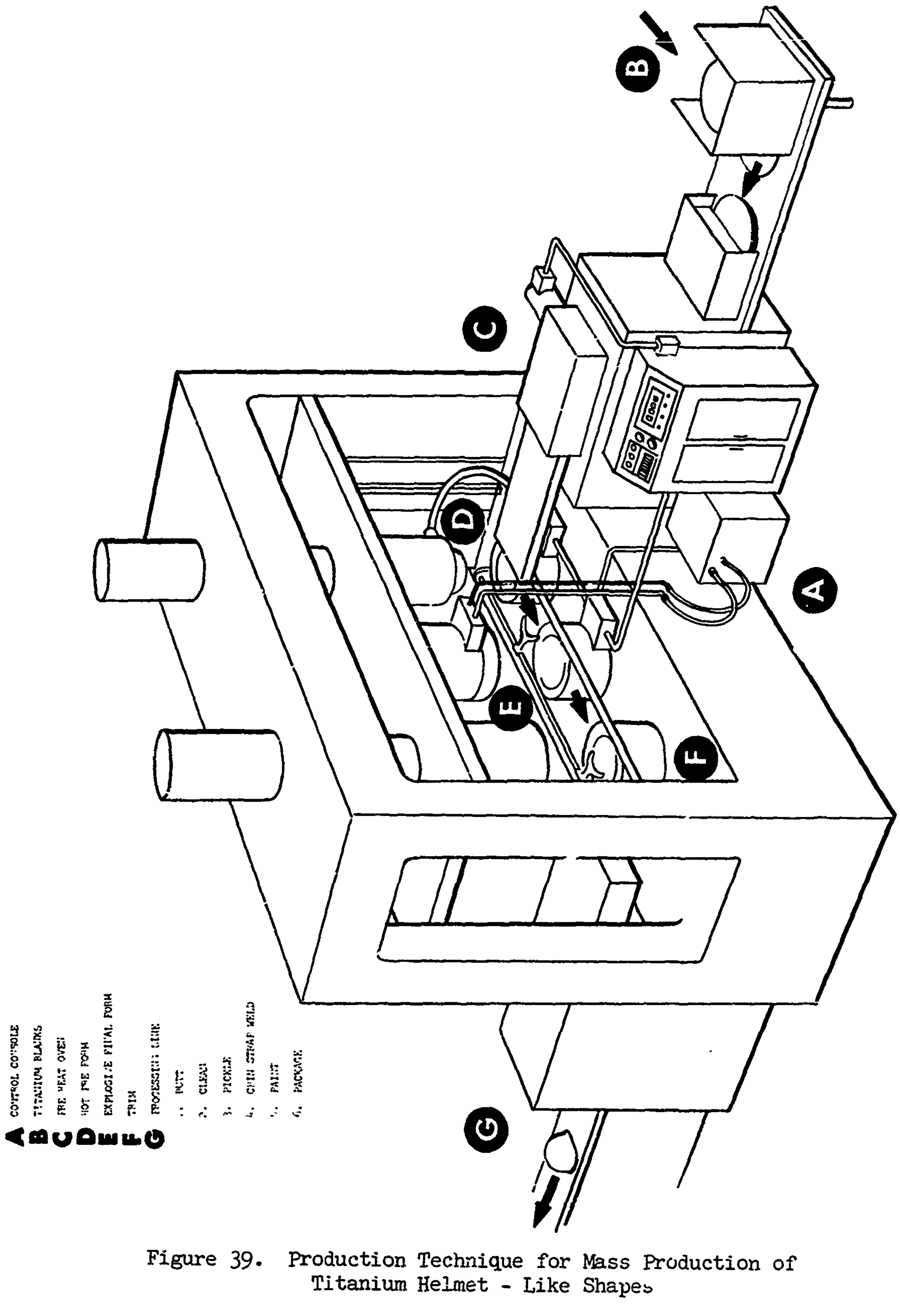


Figure 39. Production Technique for Mass Production of Titanium Helmet - Like Shapes