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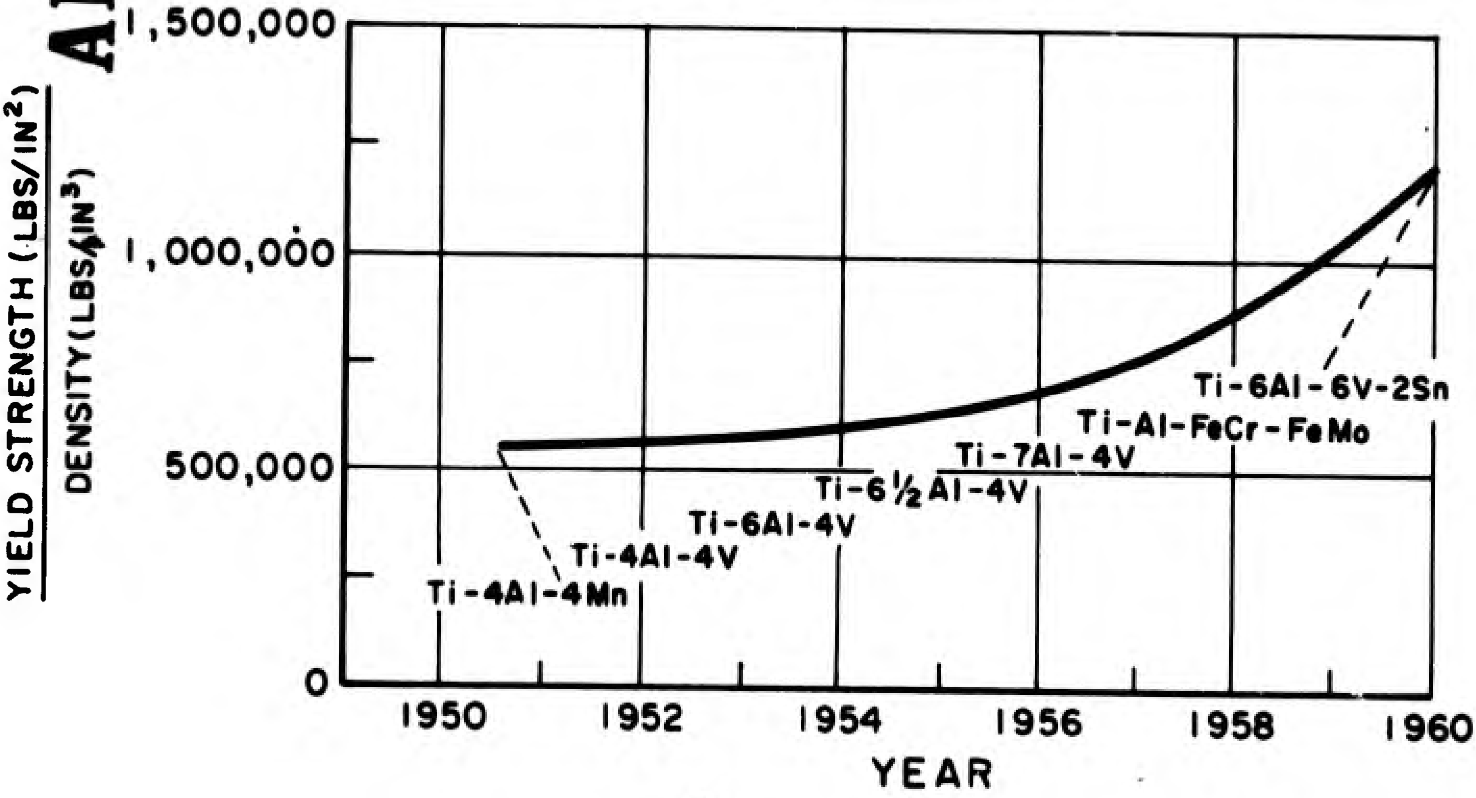
WATERTOWN ARSENAL LABORATORIES

Monograph Series

THE Ti-6Al-6V-2Sn-0.5Fe-0.25Cu ALLOY AND OTHER ALPHA-BETA TYPE ALLOYS UTILIZED AT WATERTOWN ARSENAL



By

R. M. COLTON

F. J. RIZZITANO

12-13 SEPTEMBER 1960

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THE Ti-6Al-6V-2Sn-0.5Fe-0.25Cu ALLOY AND OTHER ALPHA-BETA TYPE ALLOYS UTILIZED AT WATERTOWN ARSENAL

By

R. M. COLTON

F. J. RIZZITANO

Abstract of

Technical Presentation to be given at

New York University

Sixth Titanium Metallurgy Conference

Lecture No. 11

12-13 SEPTEMBER 1960

THE Ti-6Al-6V-2Sn-0.5Fe-0.25Cu ALLOY AND OTHER ALPHA-BETA TYPE ALLOYS UTILIZED AT WATERTOWN ARSENAL

ABSTRACT

I Introduction

During the past four or five years Watertown Arsenal has been actively engaged in the development, evaluation and exploitation of medium and high strength alpha-beta type titanium alloys. A large portion of the development work has been carried out at New York University under the auspices of Watertown Arsenal. At the present time several experimental alloys have exhibited yield strengths in excess of 200,000 psi while maintaining good ductility and toughness. Figure 1 lists a number of the most promising alloys evaluated and their corresponding mechanical property values.

The development and evaluation of the alloys were predicated on existing and contemplated Ordnance Corps material requirements for weapons systems.

Several of the alpha-beta alloys studied, including the Ti-6Al-6V-2Sn-0.5Fe-0.25Cu alloy developed at New York University, the Ti-Al-FeCr-FeMo developed at Titanium Metals Corporation of America, and the Ti-6Al-4V alloy initially studied at Watertown Arsenal are currently being utilized in such weapons systems.

II Mechanical Properties

Figure 2 shows the versatility of the Ti-6Al-6V-2Sn-0.5Fe-0.25Cu alloy. It is useful as a medium (130,000-169,999 psi yield strength) as well as a high (170,000-189,999 psi yield strength) strength material requiring toughness and ductility.

III Ordnance Corps Utilization of Alpha-Beta Type Titanium Alloys - Experimental Applications

1. Current Applications

   a. Gun Components - Ti-6Al-6V-2Sn-0.5Fe-0.25Cu at 170,000 psi yield strength.

      Figure 3 - Barrel Extrusion and Machined Barrel
      Figure 4 - Chamber Expanded Extrusion and Nozzle Forging
      Figure 5 - Table II Typical Metallurgical Properties of Above Forgings and Estrusions Processed for Alpha-Beta Type Titanium Alloys

   b. Ammunition Components - Ti-6Al-6V-2Sn-0.5Fe-0.25Cu at 170,000 psi yield strength and Ti-6Al-4V at 140,000 psi yield strength.

      Figure 6 - Reverse Extrusions
      Figure 7 - Reverse Extrusions
      Figure 8 - Closed Die Forgings
      Figure 9 - Reverse Extrusions
      Figure 10 - Closed Die Forgings

Figure 5 - Table II Typical Metallurgical Properties of Above Forgings and Extrusions Processed for Alpha-Beta Type Titanium Alloys

c. Vehicular Systems - Ti-7Al-4V at 150,000 psi yield strength and Ti-6Al-4V at 130,000 psi yield strength.
Figure 11 - Tank Track Components

d. Rapid Fire Weapons
Figure 12 - Gatling Gun Indexing and Holding Bracket
Figure 5 - Table II Typical Metallurgical Properties of Above Forgings and Extrusions Processed for Alpha-Beta Type Titanium Alloys

2. Future Applications

a. Rocket Motor Casings and Missiles

b. Armor

IV Processing and Fabrication of Components

1. Forging

a. Closed Die

b. Open Die

c. Ring Rolling

2. Extrusion

a. Forward

b. Reverse

3. Cold Forming

a. Shear Spinning

b. High Energy Rate Forming

c. Tube Reducing

4. Joining

a. Fusion Welding

b. Pressure Welding
   - Figure 13 - Pressure Welding Equipment
   - Figure 14 - Pressure Welding in Operation
   - Figure 15 - Pressure Welded Ammunition Component
   - Figure 16 - Mechanical Properties of Pressure Welded Ammunition Component - Weld and Base Material
   - Figure 17 - Macrostructure of Pressure Welded Joint
   - Figure 18 - Microstructure of Pressure Welded Joint

V Design and Testing Considerations for High-Strength Titanium Applications

1. Notch Sensitivity
   Figure 19 - Effect of Notch Radius on Impact Values for V-Notch Charpy Impact Specimens Tested at -40°F

2. Testing of Thin Sections
   Figure 20 - Effect of V-Notch Carpy Specimen Size on Impact Level Tested at -40°F

3. Ring and Cylinder Tests
   Figure 21 - Compression Test on Thin-Walled Pressure Welded Cylinder - 93% Weld Efficiency
   Figure 22 - Compression Test on Thin-Walled Pressure Welded Cylinder - 100% Weld Efficiency

VI Future Plans at Watertown Arsenal

1. Fabrication of Pressure Welded Rocket Motor Casings

2. Continued Evaluation of High Strength Alpha-Beta Type Titanium Alloys (Extensive data on most phases discussed in this presentation are available upon request at Watertown Arsenal.)

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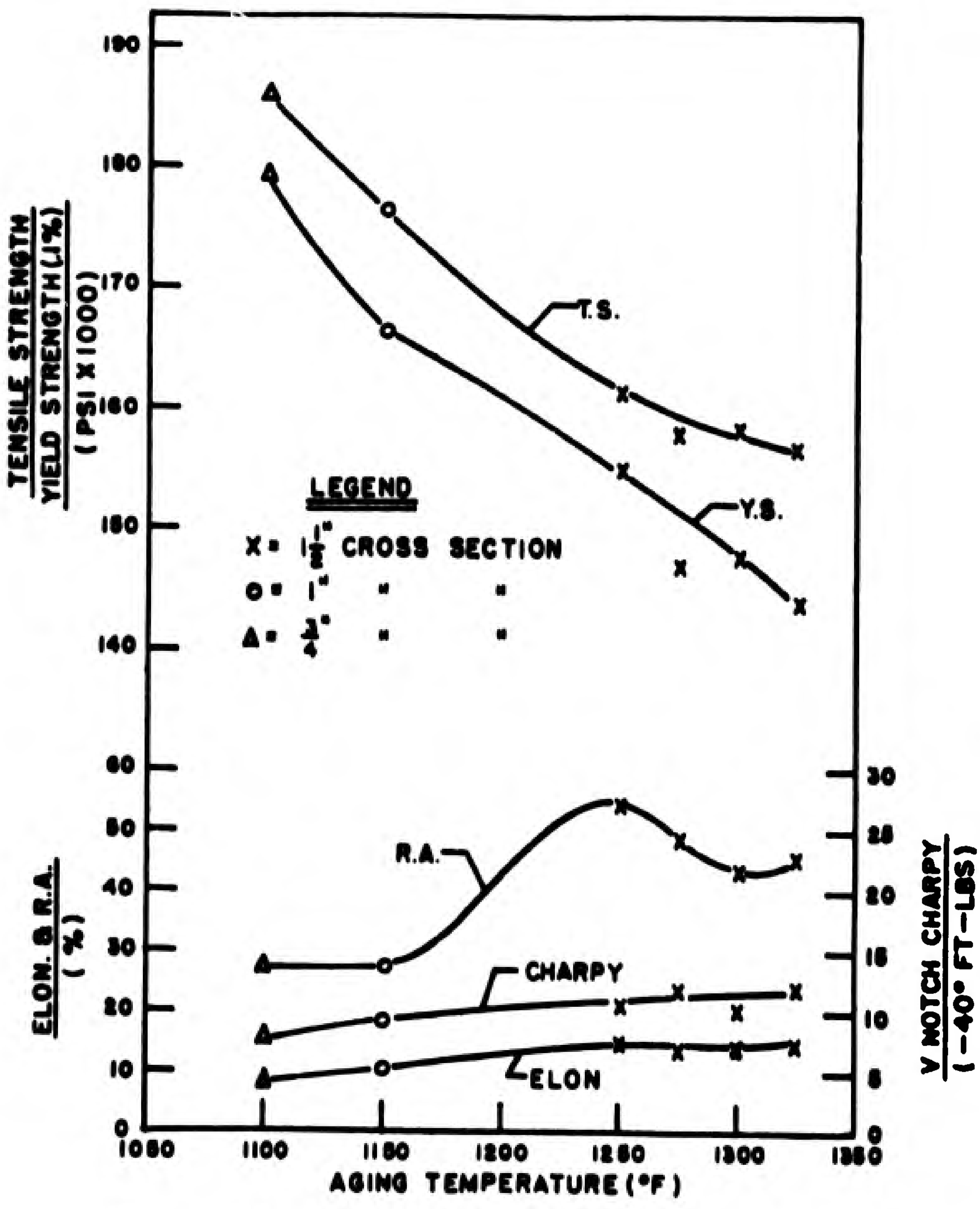
LIST OF FIGURES

LIST OF FIGURES (Cont)

PROMISING HIGH STRENGTH ALPHA-BETA TYPE TITANIUM ALLOYS

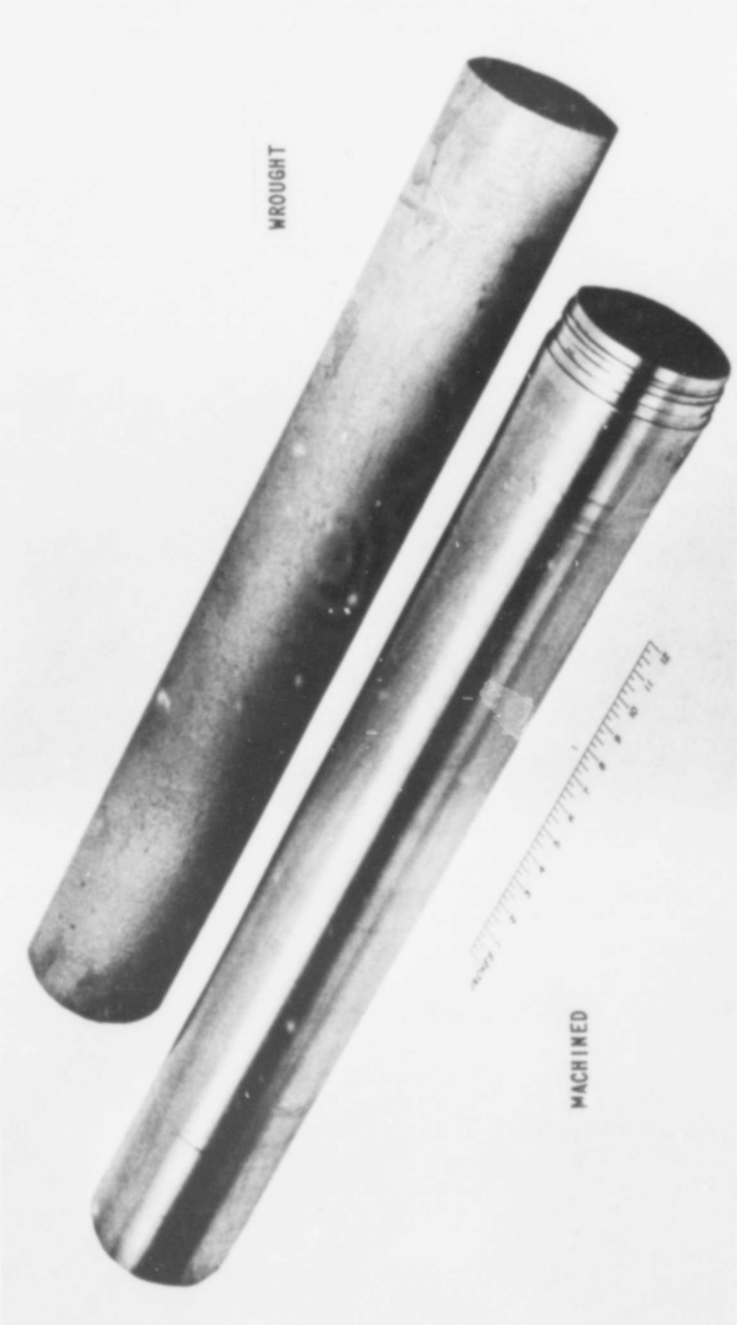
ALLOY COMPOSITION	YIELD STRENGTH (.1% OFFSET) (PSI)	ELON. (%)	R.A. (%)	V-NOTCH CHARPY IMPACT AT -40°F (FT-LBS)
Ti-Al-V-Sn-Zr-Cu-Mn	208,500	7.9	17.8	6.9
	197,500	9.7	25.3	7.7
	181,500	14.1	42.0	9.9
Ti-Al-V-Sn-Zr-Fe-Ni	204,000	7.1	21.6	8.4
	198,500	8.1	33.6	9.6
	178,000	10.8	35.2	10.7
Ti-Al-V-Sn-Zr-Cu-Fe	203,000	7.2	26.1	9.6
	188,000	11.8	37.1	9.9
	185,000	9.7	34.2	11.0
Ti-Al-V-Sn-Zr-Cu-Fe-Cr-Mo	203,000	6.8	23.0	8.6
	197,000	10.9	32.1	7.7
	182,500	12.8	46.1	12.3

FIGURE 1



AGING TEMPERATURE VERSUS MECHANICAL PROPERTIES OF 6Al-6V-2Sn TITANIUM ALLOY AT VARIOUS CROSS SECTIONAL THICKNESSES (DATA REPORTED BY FACILITY E)

FIGURE 2



FORWARD EXTRUSIONS

FIGURE 3

EXPANDED FORWARD
EXTRUSION

FORGING

FIGURE 4

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TYPICAL METALLURGICAL PROPERTIES

OF FORGINGS AND EXTRUSIONS PROCESSED FROM ALPHA-BETA TYPE TITANIUM ALLOYS

—— *IN ACCORDANCE WITH* ——

MILITARY SPECIFICATION MIL-T-46035 (ORD)

TITANIUM ALLOY, HIGH-STRENGTH WROUGHT (PROCESS)

TABLE II

WATERTOWN ARSENAL LABORATORIES

DATE *1 APRIL 1960*

SHEET *1* OF *4*

YIELD STRENGTH RANGE 120,000 – 169,999 P.S.I. (TRANSVERSE TEST PROPERTIES)

					BILLET		*FORGING AND HEAT TREAT*					*MECHANICAL PROPERTIES*					
	PROCESSOR	PRODUCER & HEAT NO	NOMINAL ANALYSIS	PART NO	DIAMETER (INCHES)	WEIGHT (LBS)	FORGING TEMPERATURE (°F) & COOLING MEDIA	TYPICAL FORGING OR EXTRUSION SECTION SIZE (INCHES)	TYPE OF WROUGHT PRODUCT	SOLUTION TREATMENT (°F)	AGING TREATMENT (°F)	SPECIFIED YS (.1%) RANGE REQUIREMENT (PSI)	ACTUAL .1% YS (PSI)	TENSILE STRENGTH (PSI)	ELONGATION (%)	RED A (%)	V-NOTCH CHARPY IMPACT AT -40°F (FT-LBS)
1	WTN ARSENAL	E-44	6.5-Al-4V	166	4½	29	1750 – WQ	1	BACKWARD EXTRUSION	1700-1½HR-WQ	1100-2HR-AC	143,000 – 162,999	161,000	173,600	14.0	41.0	10.8
2	"	"	"	"	"	"	"	"	"	"	"	"	163,000	172,800	12.0	41.0	10.6
3	"	"	"	"	"	"	"	"	"	"	"	"	160,500	170,800	17.0	42.4	10.2
4	"	"	"	"	"	"	"	"	"	"	"	"	161,000	173,400	15.0	43.4	10.7
5	"	"	"	"	"	"	"	"	"	"	"	"	162,000	172,200	15.0	45.4	10.2
6	"	"	"	"	"	"	"	"	"	"	"	"	160,000	170,600	14.0	41.6	9.8
7	"	D-66	"	545	1¾	1½	"	¾	CLOSED DIE FORGING	"	1100-4HR-AC	150,000 – 169,999	161,500	166,400	13.0	33.4	12.0
8	"	"	"	"	"	"	"	"	"	"	"	"	160,000	164,400	14.0	37.8	12.3
9																	
10																	
11	WTN ARSENAL	TMCA-27	Ti-155A	680	4⅝	16	1675 – WQ	¾	CLOSED DIE FORGING	1610-1 R-WQ	1250-4HR-AC	140,000 – 159,999	148,000	152,400	17.1	28.4	12.7
12	"	"	"	"	"	"	"	"	"	"	"	"	152,000	158,800	19.3	35.8	9.8
13	"	"	"	"	"	"	"	"	"	"	"	"	153,000	156,800	15.7	28.4	11.7
14	"	"	"	"	"	"	"	"	"	"	"	"	153,500	157,200	15.7	34.8	11.1
15	"	"	"	"	"	"	"	"	"	"	"	"	153,500	163,250	17.9	46.1	10.1
16	"	"	"	"	"	"	"	"	"	"	"	"	152,500	164,250	17.1	33.1	9.8
17	"	C-C42	6.5-Al-4V	"	"	"	"	"	"	1700-1½HR-WQ	1100-4HR-AC	"	157,000	158,600	12.0	35.2	8.9
18	"	"	"	"	"	"	"	"	"	"	"	"	156,000	165,200	10.0	36.6	9.9
19	"	E-47	"	"	"	"	"	"	"	"	1050-4HR-AC	"	163,500	174,800	13.0	34.8	10.8
20	"	"	"	"	"	"	"	"	"	"	"	"	156,750	171,800	10.0	26.0	13.3
21	"	D-73	"	307	3	3½	1750 – WQ	¾	"	"	1100-4HR-AC	"	158,500	167,000	15.0	47.4	13.8
22	"	"	"	"	"	"	"	"	"	"	"	"	158,500	165,600	13.0	41.4	14.1
23	"	D-72	"	018	3	3½	"	"	"	"	"	"	155,500	162,300	15.0	38.9	12.3
24	"	"	"	"	"	"	"	1	"	"	"	"	155,500	164,800	15.7	38.9	12.0
25	"	"	"	"	"	"	"	"	"	"	"	"	151,500	165,000	14.3	37.1	11.6
26	"	D-69	"	239	2	3	"	1½	"	"	"	"	154,000	161,200	15.7	41.9	10.0
27	"	"	"	"	"	"	"	"	"	"	"	"	154,000	162,600	10.7	38.9	10.2
28	"	"	"	"	"	"	"	"	"	"	"	"	152,000	166,600	12.1	19.1	10.7
29	"	"	"	"	"	"	"	"	"	"	"	"	158,500	164,600	15.7	44.9	10.3
30																	
31																	
32	WTN ARSENAL	E-37	6.5-Al-4V	144	2½	4½	1700 – WQ	2	CLOSED DIE FORGING	1700-1HR-BQ	1100-2HR-AC	135,000 – 154,999	142,250	149,800	17.1	47.8	9.7
33	"	"	"	"	"	"	"	"	"	"	"	"	144,000	151,000	16.4	44.1	9.2
34	"	E-55	"	"	"	"	"	"	"	"	"	"	140,000	148,800	17.1	44.5	9.5
35	"	"	"	"	"	"	"	"	"	"	"	"	140,000	147,800	17.1	44.5	9.5
36	"	E-40	"	153	3	11	2000 – WQ	1½	"	—	1300-2HR-AC	125,000 – 144,999	141,500	157,200	11.4	22.1	11.7
37	"	"	"	"	"	"	"	"	"	—	"	"	140,500	155,200	11.4	24.6	11.1
38	"	E-54	"	163	8½	85	1750 – WQ	1	BACKWARD EXTRUSION	1675-1½HR-WQ	1200-3HR-AC	135,000 – 154,999	143,000	154,000	15.7	44.1	10.0
39	"	"	"	"	"	"	"	"	"	"	"	"	146,000	154,750	14.3	34.0	10.9
40	"	"	"	"	"	"	"	"	"	"	"	"	147,000	155,500	12.1	37.1	10.5
41	"	"	"	"	"	"	"	"	"	"	"	"	144,500	153,750	14.3	38.9	10.8
42	"	E-39	"	141	2	1½	"	1½	CLOSED DIE FORGING	—	1250-2HR-AC	125,000 – 144,999	143,500	156,800	15.0	41.0	11.1
43	"	"	"	"	"	"	"	"	"	—	"	"	143,000	158,800	15.8	44.0	10.3
44	"	E-37	"	"	"	"	"	"	"	—	"	"	146,000	157,200	15.0	41.0	9.8
45	"	"	"	"	"	"	"	"	"	—	"	"	145,000	157,200	15.0	44.0	10.2
46	"	"	"	"	"	"	"	"	"	—	"	"	141,000	156,400	15.0	42.8	10.9
47	"	"	"	"	"	"	"	"	"	—	"	"	141,000	156,600	14.5	42.4	11.4
48	"	E-39	"	127	"	2½	"	"	"	—	"	"	143,000	154,800	16.0	38.6	10.1
49	"	"	"	"	"	"	"	"	"	—	"	"	144,500	155,200	15.5	38.6	10.0
50																	
51																	
52	WTN ARSENAL	E-39	6.5-Al-4V	127	2	2½	1750 – WQ	1½	CLOSED DIE FORGING	—	1250-2HR-AC	125,000 – 144,999	136,500	151,200	15.0	41.6	10.1
53	"	"	"	"	"	"	"	"	"	—	"	"	138,000	150,800	16.8	44.0	10.1
54	"	E-40	"	153	3	11	2000 – WQ	"	"	—	1300-2HR-AC	"	137,500	153,250	13.6	22.1	10.3
55	"	"	"	"	"	"	"	"	"	—	"	"	136,500	153,250	14.3	23.1	10.9
56	"	E-54	"	163	8½	85	1750 – WQ	1	BACKWARD EXTRUSION	1675-1½HR-WQ	1200-3HR-AC	135,000 – 154,999	138,000	149,800	11.4	24.1	11.2
57	"	"	"	"	"	"	"	"	"	"	"	"	139,500	148,400	12.1	34.9	10.9
58	"	E-55	"	164	"	"	"	"	"	"	"	"	136,000	147,600	10.7	24.6	12.8
59	"	"	"	"	"	"	"	"	"	"	"	"	135,000	145,000	12.1	28.4	13.0
60	"	"	"	"	"	"	"	"	"	"	"	"	138,500	150,250	15.7	27.0	11.2
61	"	"	"	"	"	"	"	"	"	"	"	"	137,000	149,500	14.3	27.5	11.5
62	"	"	"	"	"	"	"	"	"	"	"	"	139,000	151,500	10.0	24.1	12.0
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q

TYPICAL METALLURGICAL PROPERTIES

OF FORGINGS AND EXTRUSIONS PROCESSED FROM ALPHA-BETA TYPE TITANIUM ALLOYS

——IN ACCORDANCE WITH——

MILITARY SPECIFICATION MIL-T-46035 (ORD)
TITANIUM ALLOY, HIGH-STRENGTH WROUGHT (PROCESS)

TABLE II

WATERTOWN ARSENAL LABORATORIES

DATE: *1 APRIL 1960*

SHEET **2** OF **4**

YIELD STRENGTH RANGE 120,000-169,999 P.S.I. (TRANSVERSE TEST PROPERTIES)

					BILLET		FORGING AND HEAT TREAT					MECHANICAL PROPERTIES					
	PROCESSOR	PRODUCER & HEAT NO.	NOMINAL ANALYSIS	PART NO	DIAMETER (INCHES)	WEIGHT (LBS)	FORGING TEMPERATURE (°F) & COOLING MEDIA	TYPICAL FORGING OR EXTRUSION SECTION SIZE (INCHES)	TYPE OF WROUGHT PRODUCT	SOLUTION TREATMENT (°F)	AGING TREATMENT (°F)	SPECIFIED YS (.1%) RANGE REQUIREMENT (PSI)	ACTUAL .1% YS (PSI)	TENSILE STRENGTH (PSI)	ELONGATION (%)	RED A (%)	V-NOTCH CHARPY IMPACT AT -40°F (FT-LBS)
1	WTN ARSENAL	E-48	6.5Al-4V	586	8½	85	1750 - AC	1½	BACKWARD EXTRUSION	1750-2HR-WQ	1200-4HR-AC	125,000-144,999	127,500	139,250	14.3	31.2	11.0
2	"	"	"	"	"	"	"	"	"	"	"	"	129,500	140,750	14.3	32.6	12.0
3	"	"	"	"	"	"	"	"	"	"	"	"	127,000	137,000	13.6	39.4	12.5
4	"	"	"	"	"	"	"	"	"	"	"	"	125,000	135,500	13.6	36.3	11.7
5	"	E-47	"	106	"	"	"	"	"	"	"	"	127,500	143,000	17.9	34.9	11.8
6	"	"	"	"	"	"	"	"	"	"	"	"	126,750	143,000	19.3	38.9	12.7
7	"	"	"	"	"	"	"	"	"	"	"	"	126,000	145,500	19.0	32.2	11.2
8	"	"	"	"	"	"	"	"	"	"	"	"	130,500	147,000	14.3	32.6	12.1
9	"	E-39	"	142	8	30	"	2	CLOSED DIE FORGING	—	1050-3HR-AC	"	129,000	135,000	16.4	41.6	12.7
10	"	"	"	"	"	"	"	"	"	—	"	"	127,500	137,400	19.3	42.4	12.7
11	"	"	"	"	"	"	"	"	"	—	"	"	128,000	136,600	19.7	43.6	13.3
12	"	"	"	"	"	"	"	"	"	—	"	"	129,000	139,000	17.9	41.9	12.4
13																	
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TYPICAL METALLURGICAL PROPERTIES
OF FORGINGS AND EXTRUSIONS PROCESSED FROM ALPHA-BETA TYPE TITANIUM ALLOYS

— *IN ACCORDANCE WITH* —

MILITARY SPECIFICATION MIL-T-46035 (ORD)
TITANIUM ALLOY, HIGH-STRENGTH WROUGHT (PROCESS)

TABLE II

WATERTOWN ARSENAL LABORATORIES

DATE *1 APRIL 1960*

SHEET *3* OF *4*

YIELD STRENGTH RANGE 160,000 - 189,999 P.S.I. (TRANSVERSE TEST PROPERTIES)

					BILLET		*FORGING AND HEAT TREAT*						*MECHANICAL PROPERTIES*				
	PROCESSOR	PRODUCER & HEAT NO	NOMINAL ANALYSIS	PART NO	DIAMETER (INCHES)	WEIGHT (LBS)	FORGING TEMPERATURE (°F) & COOLING MEDIA	TYPICAL FORGING OR EXTRUSION SECTION SIZE (INCHES)	TYPE OF WROUGHT PRODUCT	SOLUTION TREATMENT (°F)	AGING TREATMENT (°F)	SPECIFIED YS (1%) RANGE REQUIREMENT (P.S.I.)	ACTUAL 1% Y.S. (P.S.I.)	TENSILE STRENGTH (P.S.I.)	ELONGATION (%)	RED. A (%)	V-NOTCH CHARPY IMPACT AT -40°F (FT-LBS)
1	G	B-17	6Al-6V-~~[illegible]~~ 2Sn	605	10½	220	1675 (MAX) - AC	½	FORWARD EXTRUSION	1630-½HR-WQ	1050-4HR-AC	170,000 - 189,999	188,400	196,500	6.7	9.0	6.5
2	G	"	"	"	"	"	"	"	"	"	"	"	188,300	196,300	9.3	11.5	6.5
3	G	"	"	"	"	"	"	"	"	"	"	"	185,800	195,000	6.7	20.6	7.0
4	G	"	"	"	"	"	"	"	"	"	"	"	181,600	192,000	9.3	17.4	6.5
5	G	"	"	"	"	"	"	"	"	"	"	"	184,100	194,000	8.0	16.9	6.0
6	G	"	"	"	"	"	"	"	"	"	"	"	190,100	196,000	9.3	15.4	7.0
7	G	"	"	"	"	"	"	"	"	"	"	"	187,600	197,500	8.0	19.9	7.0
8	G	"	"	"	"	"	"	"	"	"	"	"	189,100	201,500	6.7	11.9	7.8
9	G	"	"	"	"	"	"	"	"	"	"	"	187,600	199,800	6.7	16.4	6.0
10	G	"	"	"	"	"	"	"	"	"	"	"	187,100	198,300	6.7	14.4	7.0
11	G	"	"	"	"	"	"	"	"	"	1100-4HR-AC	"	178,000	—	10.9	21.4	6.7
12	G	"	"	"	"	"	"	"	"	"	"	"	180,500	—	7.8	17.6	7.3
13	G	"	"	"	"	"	"	"	"	"	"	"	188,000	—	7.8	16.9	7.0
14	G	"	"	"	"	"	"	"	"	"	"	"	181,000	—	9.4	17.9	6.0
15	G	"	"	"	"	"	"	"	"	"	"	"	171,000	—	9.4	19.9	7.3
16	G	"	"	"	"	"	"	"	"	"	"	"	181,000	—	9.4	17.9	7.3
17	G	A-46-2	"	"	"	"	"	"	"	"	"	"	172,800	188,000	7.8	18.4	9.2
18	G	"	"	"	"	"	"	"	"	"	"	"	172,200	183,800	6.3	14.4	7.6
19	G	"	"	"	"	"	"	"	"	"	"	"	17[illegible],000	188,000	9.4	23.4	8.8
20	G	"	"	"	"	"	"	"	"	"	"	"	176,[illegible]00	190,000	4.7	11.9	8.1
21	G	"	"	"	"	"	"	"	"	"	"	"	174,[illegible]00	186,500	9.4	19.9	8.5
22	G	"	"	"	"	"	"	"	"	"	"	"	170,000	186,000	6.3	11.9	8.9
23	G	A-46-D1	"	"	"	"	"	"	"	"	"	"	180,000	188,000	7.8	22.8	9.2
24	G	"	"	"	"	"	"	"	"	"	"	"	173,000	186,000	6.3	16.9	8.8
25	G	"	"	"	"	"	"	"	"	"	"	"	175,000	190,000	7.8	17.9	9.0
26	G	"	"	"	"	"	"	"	"	"	"	"	173,000	187,500	6.3	16.9	8.8
27	I	A-99	"	"	14	180	1675	1½	"	1650-1HR-WQ	1150-4HR-AC	"	182,500	182,500	8.8	24.0	8.4
28	I	B-00	"	"	"	"	"	"	"	"	1050-4HR-AC	"	170,500	187,500	10.0	18.9	8.0
29	I	"	"	"	"	"	"	"	"	"	"	"	169,500	185,500	10.0	20.1	8.0
30	I	B-99	"	"	"	"	1725	"	"	"	"	"	179,000	199,000	7.5	8.7	6.7
31	I	"	"	"	"	"	"	"	"	"	"	"	172,800	189,000	10.0	20.0	8.6
32	I	"	"	"	"	"	1775	"	"	[illegible]HR-WQ	[illegible]	"	170,200	187,000	2.8	15.4	7.0
33	I	"	"	"	"	"	"	"	"	[illegible]HR-WQ	1050-4HR-AC	"	160,000	181,200	6.3	20.8	8.8
34	I	B-00	"	"	"	"	1800	"	"	"	"	"	181,700	198,800	7.5	14.5	8.3
35	I	B-99	"	"	"	"	1850	"	"	"	"	"	187,900	208,700	5.0	11.2	6.6
36	I	"	"	"	"	"	"	"	"	"	"	"	188,200	199,000	7.5	15.3	6.5
37	I	"	"	"	"	"	"	"	"	1630-[illegible]	"	"	187,500	188,000	7.5	20.1	9.0
38	I	"	"	"	"	"	"	"	"	"	"	"	169,000	185,000	7.5	20.1	9.9
39	I	"	"	"	"	"	"	"	"	"	"	"	180,000	202,000	2.5	3.2	6.4
40	I	"	"	"	"	"	"	"	"	"	"	"	178,000	199,000	7.5	19.0	5.6
41	I	B-00	"	"	"	"	"	"	"	"	"	"	177,000	196,000	5.0	11.0	6.0
42	I	"	"	"	"	"	"	"	"	1680-1½HR-WQ	1150-4HR-AC	"	171,400	185,700	10.0	32.0	6.0
43	I	"	"	"	"	"	"	"	"	"	"	"	170,800	186,900	7.5	16.2	6.5
44	I	"	"	"	"	"	"	"	"	1630-1HR-WQ	"	"	163,600	184,500	8.0	11.2	9.1
45	G	TMCA-28	Ti-155A	"	10½	250	1700	½	"	1675-1½HR WQ	1100-4HR-AC	"	179,000	>190,000	7.0	23.0	6.5
46	G	"	"	"	"	"	"	"	"	"	"	"	182,000	"	8.5	18.6	7.9
47	G	"	"	"	"	"	"	"	"	"	"	"	181,000	"	9.0	24.3	7.7
48	G	"	"	"	"	"	"	"	"	"	"	"	187,000	"	9.4	25.2	7.8
49	G	"	"	"	"	"	"	"	"	"	"	"	188,000	"	8.8	24.6	7.8
50	S	"	"	"	"	"	"	"	"	"	"	"	180,000	"	8.8	20.3	7.3
51	G	"	"	"	"	"	"	"	"	"	"	"	176,000	"	7.0	22.9	6.4
52	G	"	"	"	"	"	"	"	"	"	"	"	189,000	"	7.8	16.3	7.8
53	G	"	"	"	"	"	"	"	"	"	"	"	186,000	"	7.8	17.7	8.1
54	G	"	"	"	"	"	"	"	"	"	"	"	180,000	"	8.0	21.3	8.4
55	G	"	"	"	"	"	"	"	"	"	"	"	189,000	"	8.8	23.0	6.8
56	G	"	"	"	"	"	1725	"	"	"	"	"	181,000	"	9.5	20.1	7.2
57	G	"	"	"	"	"	"	"	"	"	"	"	183,000	"	8.0	21.9	7.8
58	G	"	"	"	"	"	1750	"	"	"	"	"	173,000	"	7.5	20.0	6.8
59	G	"	"	"	"	"	"	"	"	"	"	"	183,000	"	8.0	18.4	7.4
60	G	"	"	"	"	"	"	"	"	"	"	"	183,000	"	7.1	21.3	7.3
61	G	"	"	"	"	"	"	"	"	"	"	"	185,000	"	8.6	19.1	7.8
62	G	"	"	"	"	"	"	"	"	"	"	"	177,000	"	7.3	20.1	7.2
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q

TYPICAL METALLURGICAL PROPERTIES
OF FORGINGS AND EXTRUSIONS PROCESSED FROM ALPHA-BETA TYPE TITANIUM ALLOYS

——IN ACCORDANCE WITH——

MILITARY SPECIFICATION MIL-T-46035 (ORD)
TITANIUM ALLOY, HIGH-STRENGTH WROUGHT (PROCESS)

TABLE II

WATERTOWN ARSENAL LABORATORIES

DATE: *1 APRIL 1960*

SHEET *4* OF *4*

YIELD STRENGTH RANGE 160,000 – 189,999 P.S.I. (TRANSVERSE TEST PROPERTIES)

	PROCESSOR	PRODUCER & HEAT NO	NOMINAL ANALYSIS	PART NO	BILLET DIAMETER (INCHES)	BILLET WEIGHT (LBS)	FORGING AND HEAT TREAT: FORGING TEMPERATURE (°F) & COOLING MEDIA	TYPICAL FORGING OR EXTRUSION SECTION SIZE (INCHES)	TYPE OF WROUGHT PRODUCT	SOLUTION TREATMENT (°F)	AGING TREATMENT (°F)	MECHANICAL PROPERTIES: SPECIFIED Y.S. (.1%) RANGE REQUIREMENT (P.S.I.)	ACTUAL .1% Y.S. (P.S.I.)	TENSILE STRENGTH (P.S.I.)	ELONGATION (%)	RED A (%)	V-NOTCH CHARPY IMPACT AT -40°F (FT-LBS)
1	WTN ARSENAL	TMCA-11	Ti-155A	604	3½	8	1700-WQ	[illegible]	CLOSED DIE FORGING	1610-1½HR-WQ	1100-4HR-AC	170,000-189,999	172,000	178,000	12.0	29.4	9.2
2	WTN ARSENAL	"	"	"	"	"	"	"	"	"	"	"	172,000	176,800	14.0	42.4	7.8
3	WTN ARSENAL	"	"	"	"	"	"	"	"	"	"	"	167,600	174,800	9.0	22.6	8.1
4	WTN ARSENAL	"	"	"	"	"	"	"	"	"	"	"	167,600	183,200	10.0	21.2	7.3
5	WTN ARSENAL	TMCA-80	"	"	"	"	"	"	"	1680-1½HR-WQ	"	"	180,200	188,000	9.0	26.8	8.2
6	WTN ARSENAL	TMCA-53	"	"	"	"	"	"	"	"	"	"	178,000	192,000	6.0	13.4	6.1
7	WTN ARSENAL	"	"	"	"	"	"	"	"	"	"	"	178,000	192,000	7.0	17.7	6.1
8	WTN ARSENAL	"	"	"	"	"	"	"	"	"	"	"	180,000	193,800	6.0	17.0	7.3
9	WTN ARSENAL	"	"	"	"	"	"	"	"	"	"	"	181,000	196,800	6.0	19.8	7.1
10	WTN ARSENAL	"	"	"	"	"	"	"	"	"	"	"	177,000	188,400	6.0	21.2	6.1
11	WTN ARSENAL	"	"	"	"	"	"	"	"	"	"	"	178,000	186,800	8.0	21.8	7.7
12	WTN ARSENAL	TMCA-11	"	606	"	10	"	1½	OPEN DIE FORGING	"	1050-4HR-AC	"	170,000	191,200	7.0	18.6	6.7
13	WTN ARSENAL	"	"	"	"	"	"	"	"	"	"	"	171,500	190,400	7.0	18.6	7.0
14	WTN ARSENAL	"	"	"	"	"	"	"	"	1610-1HR-WQ	"	"	170,000	181,800	12.5	23.4	6.0
15	WTN ARSENAL	"	"	"	"	"	"	"	"	"	"	"	167,500	182,000	9.4	16.9	9.8
16	H	B-20	6Al-6V-2Sn	63-B	9½	250	1750-AC	"	FORWARD EXTRUSION	1660-1½HR-WQ	1125-4HR-AC	"	174,000	186,000	6.0	12.8	7.9
17	H	"	"	"	"	"	"	"	"	"	"	"	173,000	183,000	6.1	13.2	6.1
18	H	"	"	"	"	"	"	"	"	1630-1½HR-WQ	"	"	170,000	186,000	6.1	12.8	7.8
19	H	"	"	"	"	"	"	"	"	"	"	"	170,500	186,400	6.2	13.0	7.8
20	G	B-99	"	63-C	10⅝	70	1690 (MAX)-AC	1	FORWARD EXTRUSION (EXPANDED)	"	1050-4HR-AC	"	169,000	183,800	6.0	18.4	6.9
21	G	"	"	"	"	"	"	"	"	"	"	"	178,500	188,800	9.0	29.4	6.4
22	G	"	"	"	"	"	"	"	"	"	"	"	176,000	189,200	7.0	17.0	6.7
23	G	"	"	"	"	"	"	"	"	"	"	"	176,000	187,600	7.8	21.6	6.4
24	G	"	"	"	"	"	"	"	"	"	"	"	179,000	192,000	9.0	14.7	7.8
25	G	"	"	"	"	"	"	"	"	"	"	"	176,000	188,000	8.0	18.4	6.8
26	G	"	"	"	"	"	"	"	"	"	"	"	177,500	188,400	9.0	28.4	6.6
27	G	"	"	"	"	"	"	"	"	"	"	"	174,000	188,200	9.0	22.6	6.4
28	G	"	"	"	"	"	"	"	"	"	"	"	173,000	182,800	8.0	21.8	6.4
29	G	"	"	"	"	"	"	"	"	"	"	"	171,800	181,600	11.0	33.4	6.6
30	G	"	"	"	"	"	"	"	"	"	"	"	174,300	190,200	8.5	16.9	10.0
31	G	"	"	"	"	"	"	"	"	"	"	"	171,400	189,700	9.0	14.8	—
32	G	"	"	"	"	"	"	"	"	"	"	"	184,500	202,900	6.0	13.9	6.8
33	G	"	"	"	"	"	"	"	"	"	"	"	176,300	191,900	7.0	14.6	6.8
34	G	"	"	"	"	"	"	"	"	"	"	"	181,600	197,900	7.0	12.4	6.0
35	G	"	"	"	"	"	"	"	"	"	"	"	179,800	195,800	7.5	15.3	6.0
36	WTN ARSENAL	B-20	"	63-N	6½	50	1675-WQ	1½	OPEN DIE FORGING	"	1100-4HR-AC	"	178,280	—	6.0	13.1	7.8
37	WTN ARSENAL	"	"	"	"	"	"	"	"	"	"	"	174,300	—	6.3	24.4	7.0
38	WTN ARSENAL	B-99	"	"	"	"	"	"	"	"	"	"	184,600	—	7.0	21.6	6.0
39	WTN ARSENAL	"	"	"	"	"	"	"	"	"	"	"	178,800	191,400	6.1	14.3	7.0
40	WTN ARSENAL	"	"	"	"	"	"	"	"	"	"	"	182,300	—	6.8	17.2	6.1
41	WTN ARSENAL	B-25	"	DE-2	3½	6	"	[illegible]	CLOSED DIE FORGING	"	"	"	174,000	184,800	10.0	18.2	7.3
42	WTN ARSENAL	"	"	"	"	"	"	"	"	"	"	"	174,800	186,000	10.0	27.4	7.0
43																	
44																	
45	WTN ARSENAL	TMCA-80	Ti-155A	121	6½	40	1725-WQ	1	BACKWARD EXTRUSION	1625-1½HR-WQ	1100-4HR-AC	160,000-179,999	168,500	179,200	12.0	30.2	7.0
46	WTN ARSENAL	"	"	"	"	"	"	"	"	"	"	"	168,000	184,600	10.0	22.6	6.0
47	WTN ARSENAL	"	"	"	"	"	"	"	"	"	"	"	165,000	179,000	12.8	30.8	6.4
48	WTN ARSENAL	"	"	"	"	"	"	"	"	"	"	"	164,000	177,400	13.0	27.4	6.2
49	WTN ARSENAL	A-95-1	6Al-6V-2Sn	"	"	"	"	"	"	1680-1½HR-WQ	1200-4HR-AC	"	160,000	174,000	10.0	21.2	7.0
50	WTN ARSENAL	"	"	"	"	"	"	"	"	"	"	"	165,000	176,000	6.0	17.7	7.8
51	WTN ARSENAL	"	"	"	"	"	"	"	"	"	"	"	162,500	175,400	10.0	30.8	7.8
52	WTN ARSENAL	"	"	"	"	"	"	"	"	"	"	"	162,000	172,200	13.0	30.6	6.1
53	WTN ARSENAL	TMCA-80	Ti-155A	119	"	"	"	"	"	1675-1½HR-WQ	1100-4HR-AC	"	167,500	184,000	6.4	14.0	6.8
54	WTN ARSENAL	"	"	"	"	"	"	"	"	"	"	"	170,000	180,800	6.6	23.1	7.0
55	WTN ARSENAL	"	"	"	"	"	"	"	"	"	"	"	171,500	180,500	6.7	13.0	6.7
56	WTN ARSENAL	"	"	"	"	"	"	"	"	"	"	"	172,500	183,750	7.9	18.1	6.3
57	WTN ARSENAL	"	"	"	"	"	"	"	"	"	"	"	167,000	186,250	4.3	8.7	6.2
58	WTN ARSENAL	"	"	"	"	"	"	"	"	"	"	"	168,000	184,500	7.1	11.4	5.9
59	WTN ARSENAL	A-95-1	6Al-6V-2Sn	"	"	"	"	"	"	1680-1½HR-WQ	1200-4HR-AC	"	168,000	177,500	7.9	26.5	6.1
60	WTN ARSENAL	"	"	"	"	"	"	"	"	"	"	"	166,500	177,500	10.0	28.1	6.2
61	WTN ARSENAL	"	"	"	"	"	"	"	"	"	"	"	165,000	175,000	11.4	28.4	5.5
62	WTN ARSENAL	"	"	"	"	"	"	"	"	"	"	"	165,000	175,000	10.7	24.6	5.7
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q

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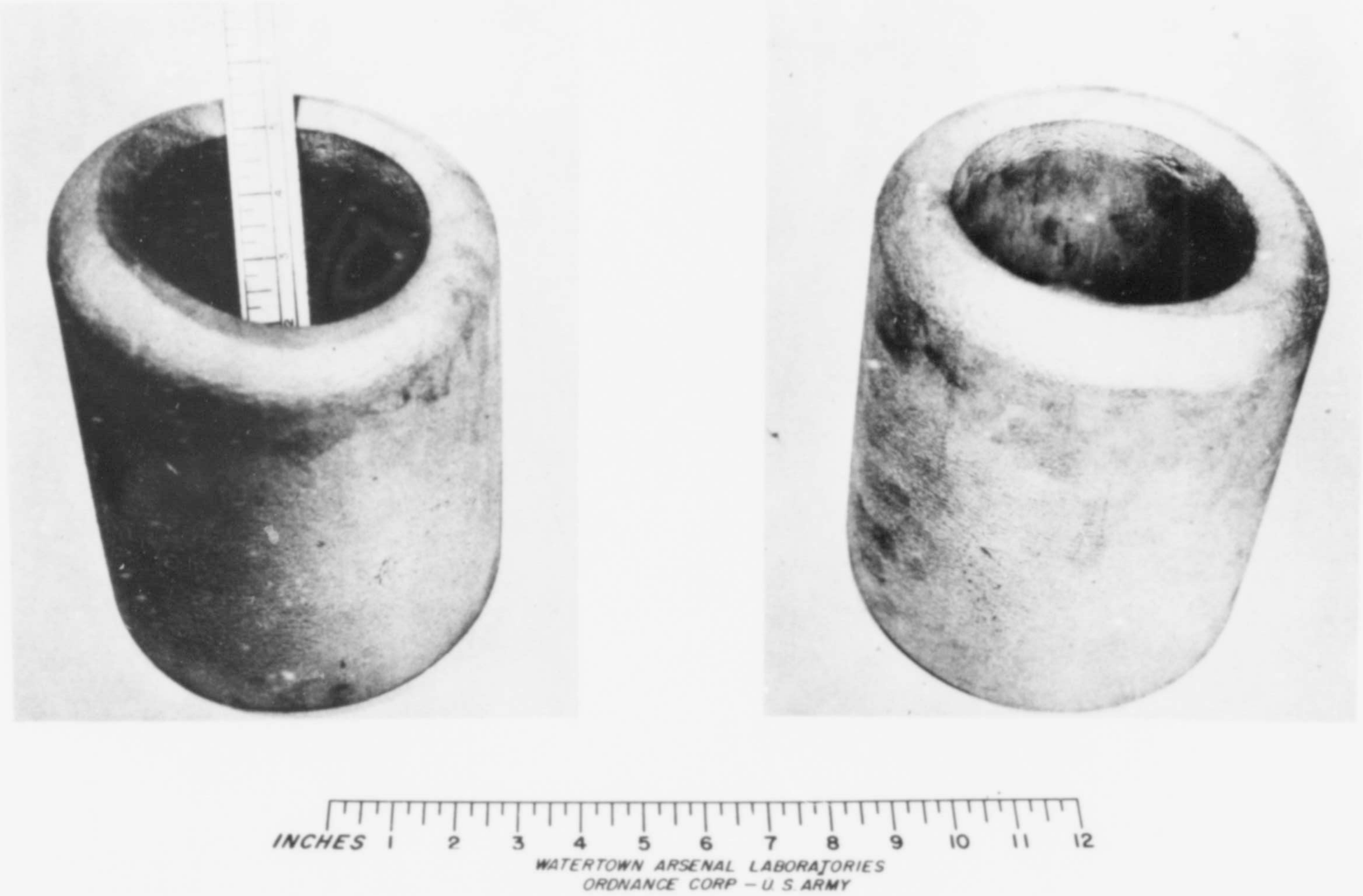
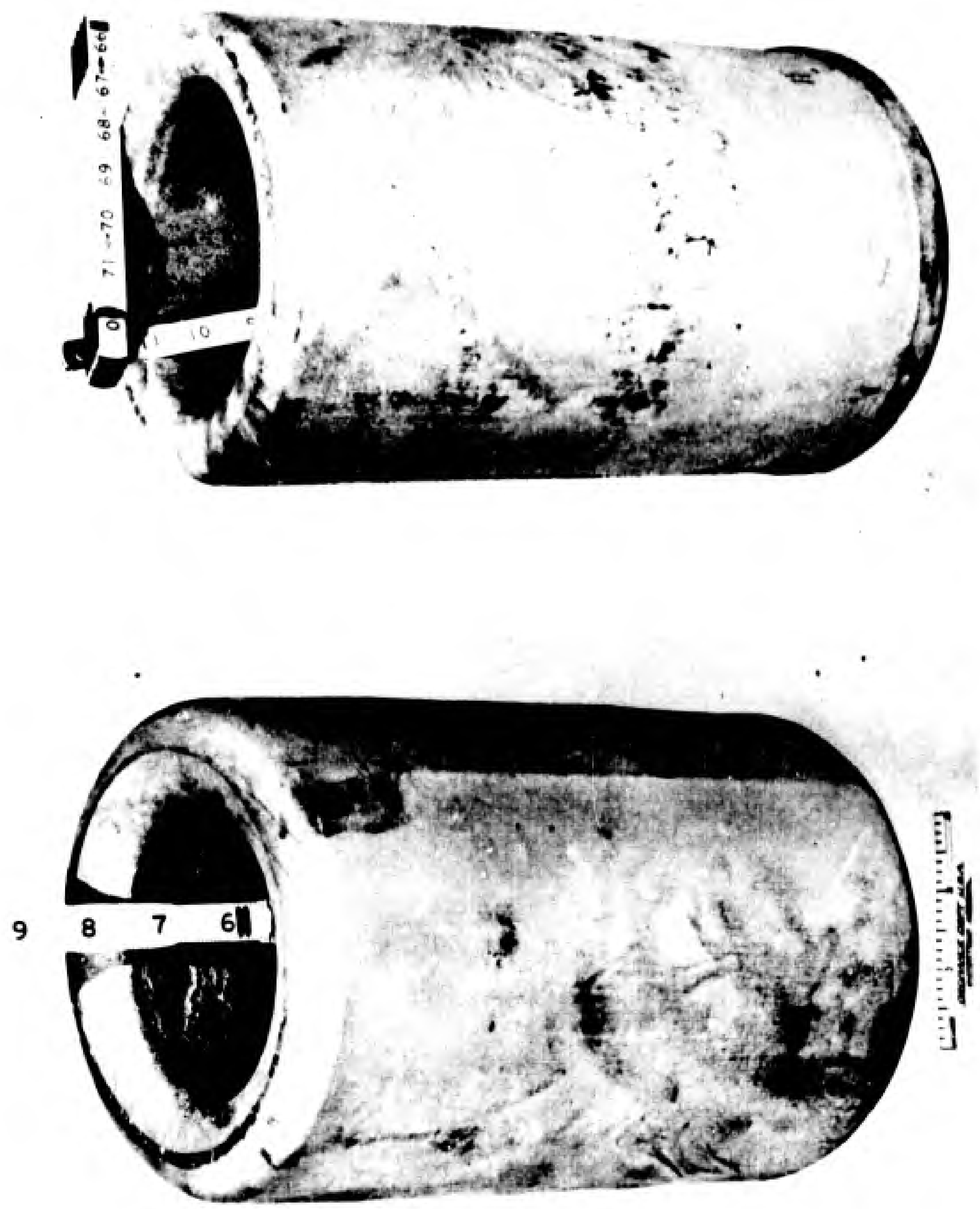


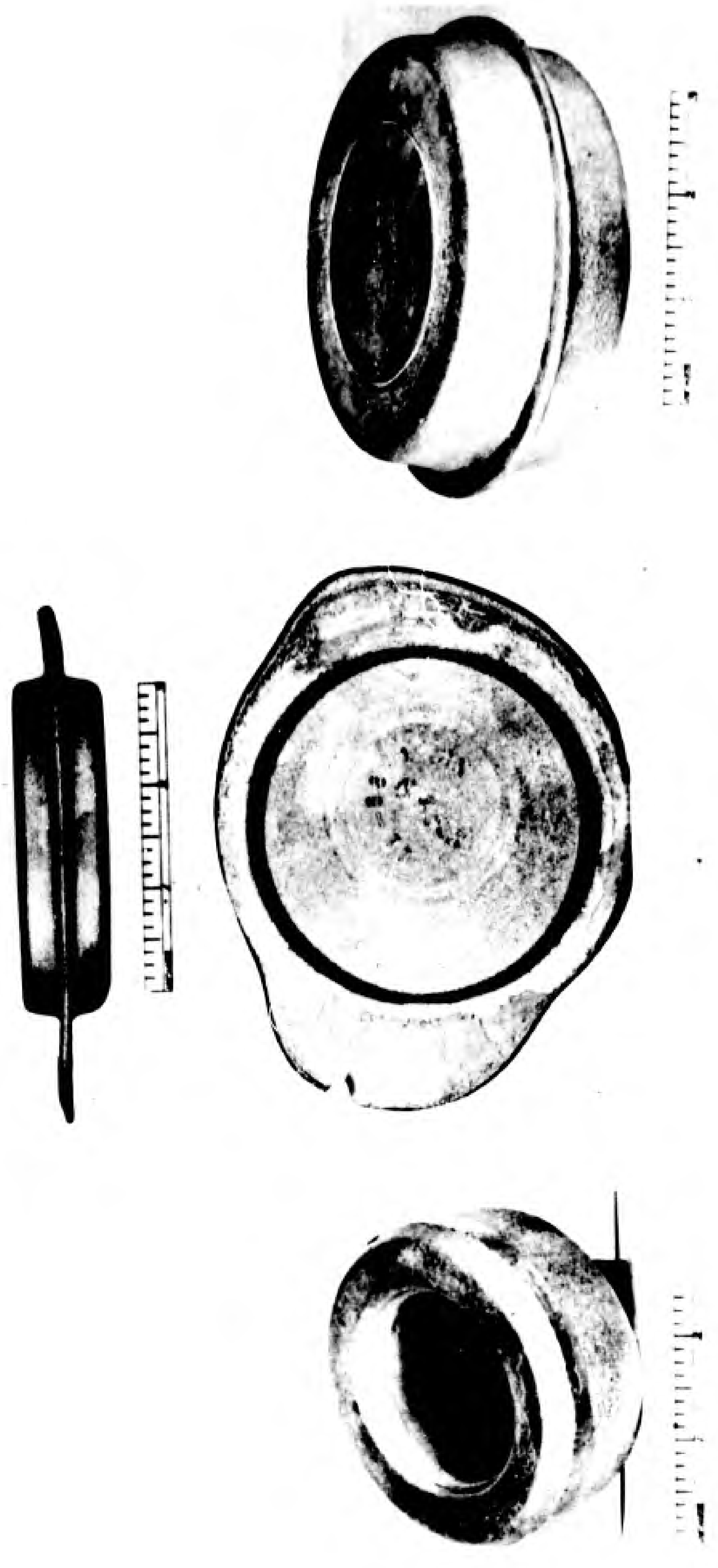
REVERSE EXTRUSIONS

FIGURE 6



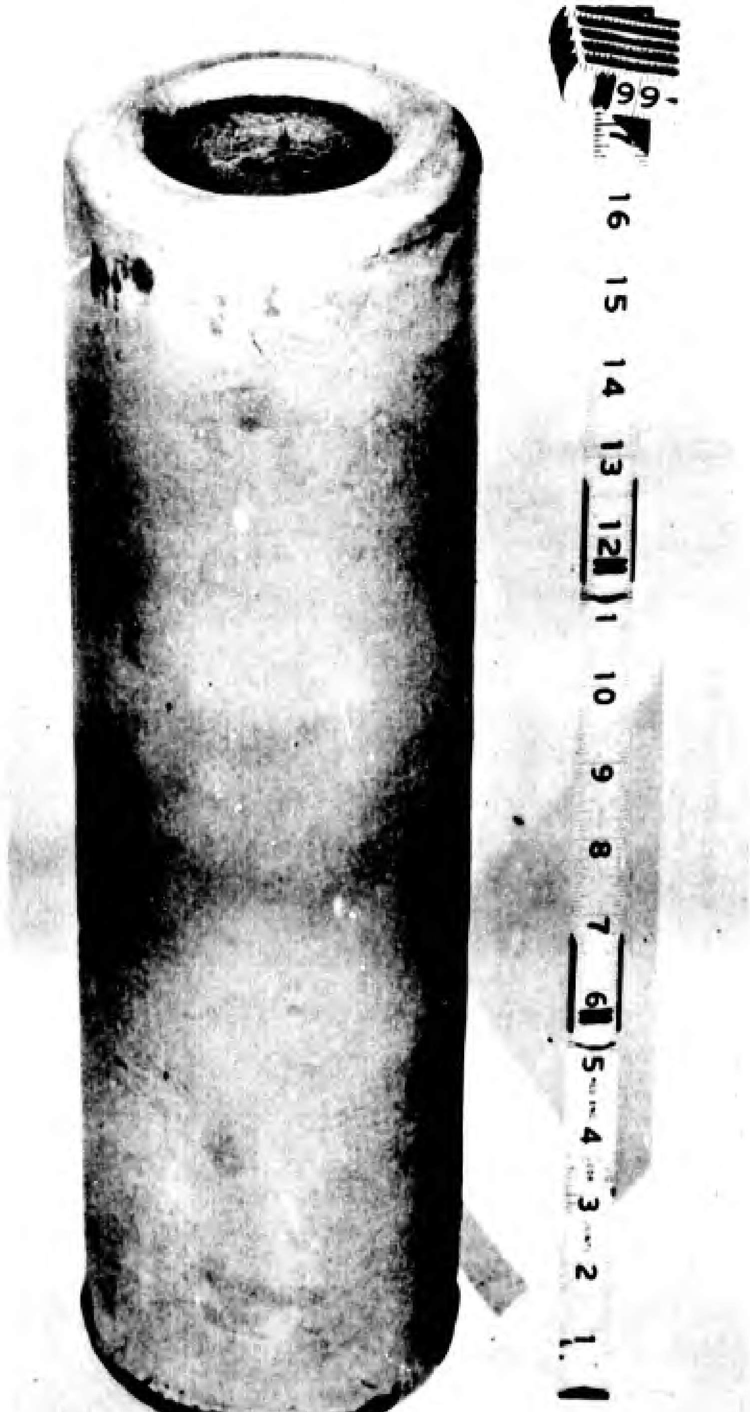
REVERSE EXTRUSIONS

FIGURE 7



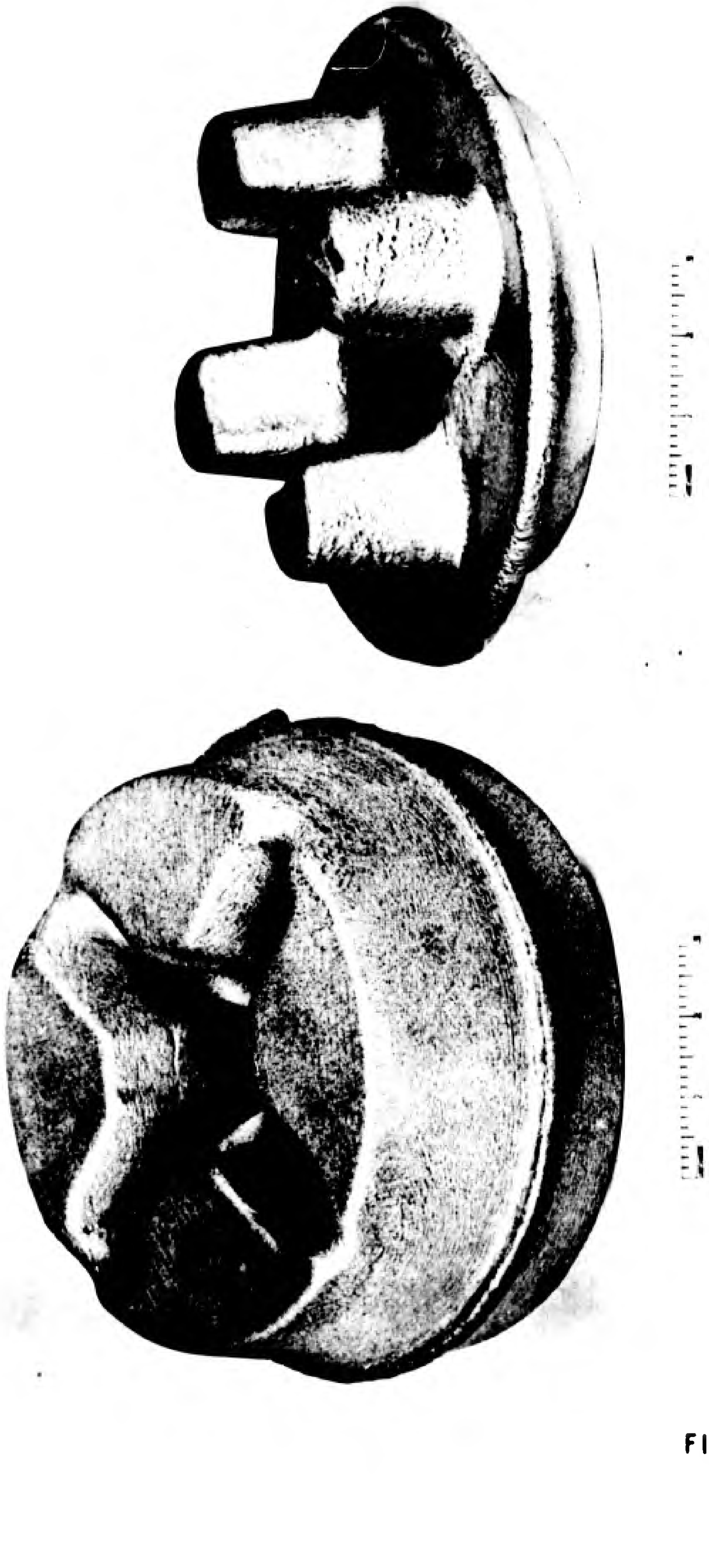
CLOSED DIE FORGINGS

FIGURE 8



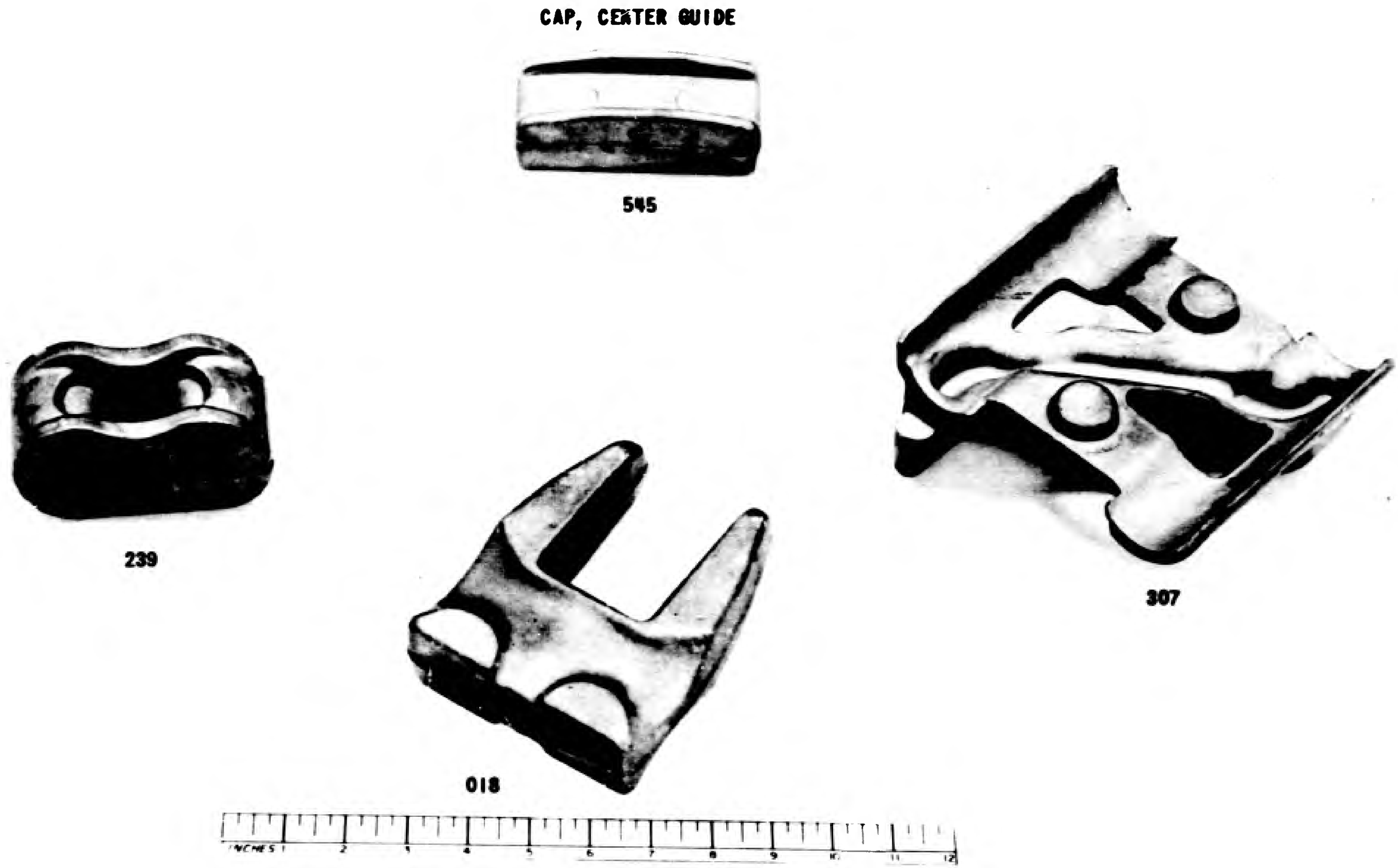
REVERSE EXTRUSION

FIGURE 9



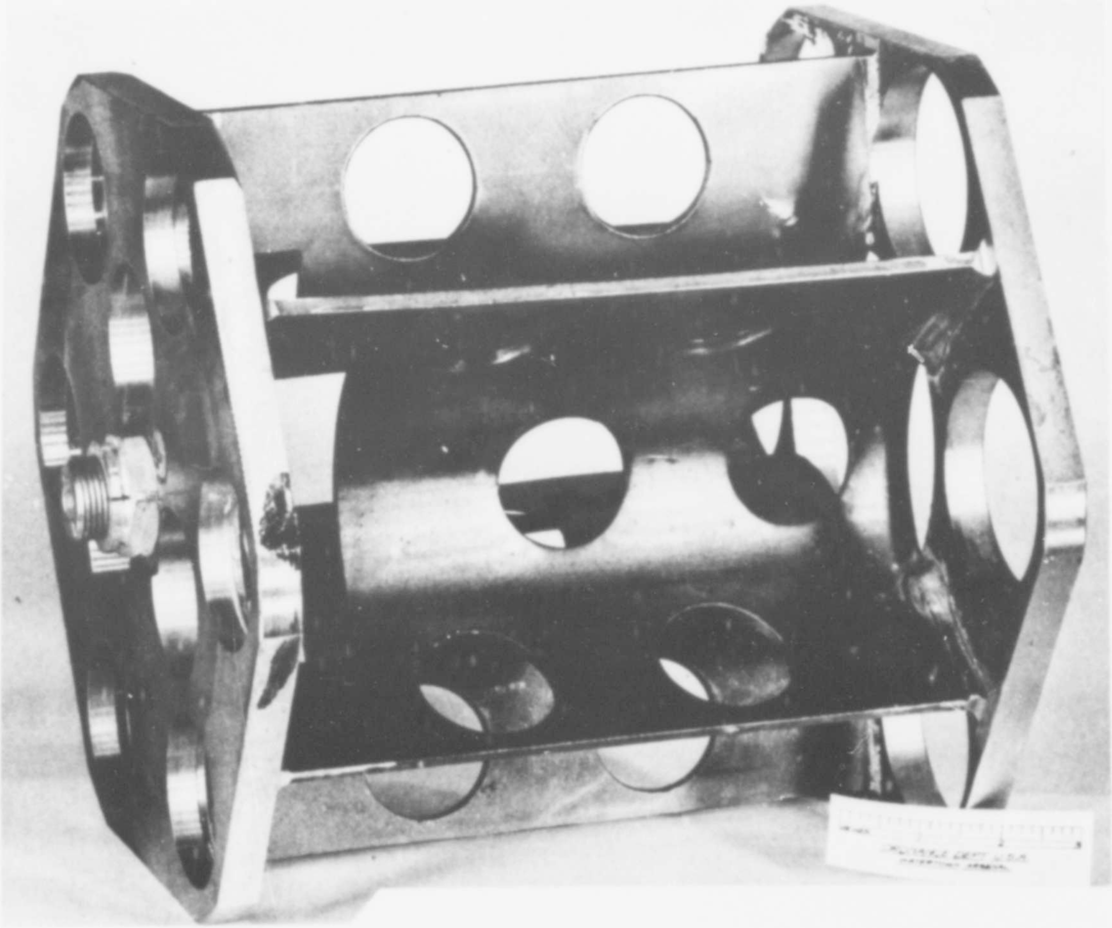
CLOSED DIE FORGINGS

FIGURE 10



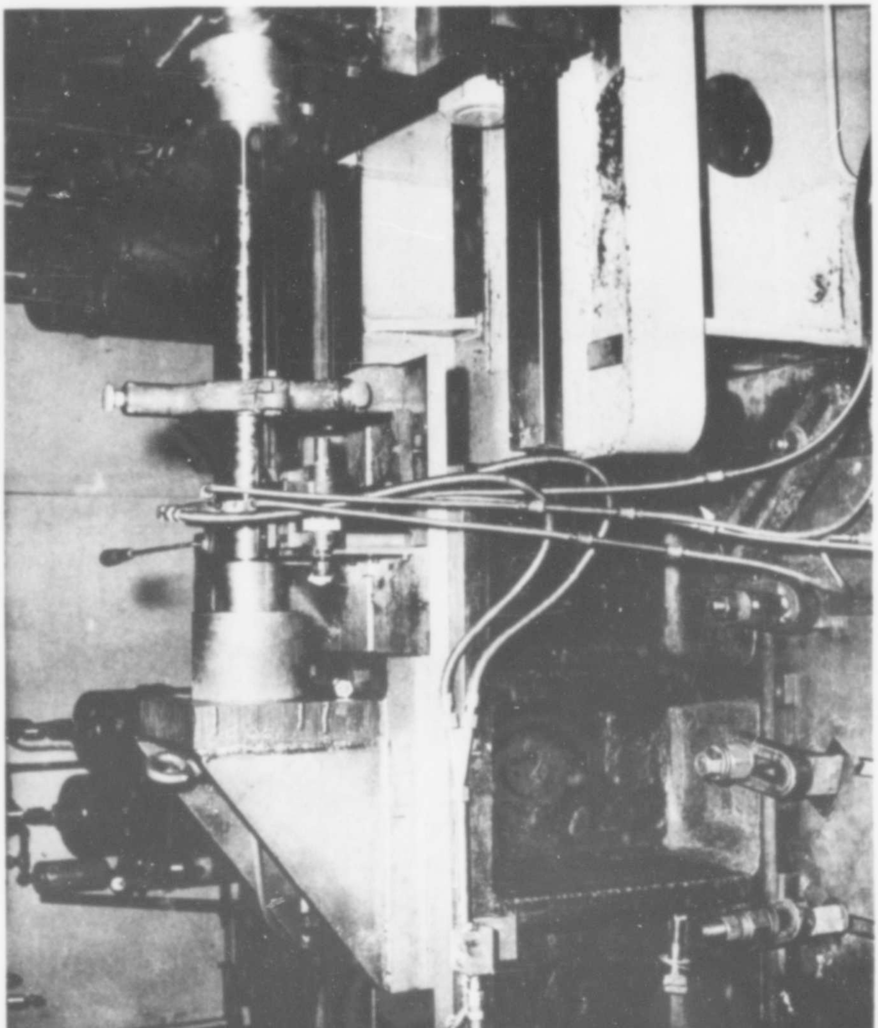
FORGED TITANIUM TANK TRACK COMPONENTS

FIGURE 11



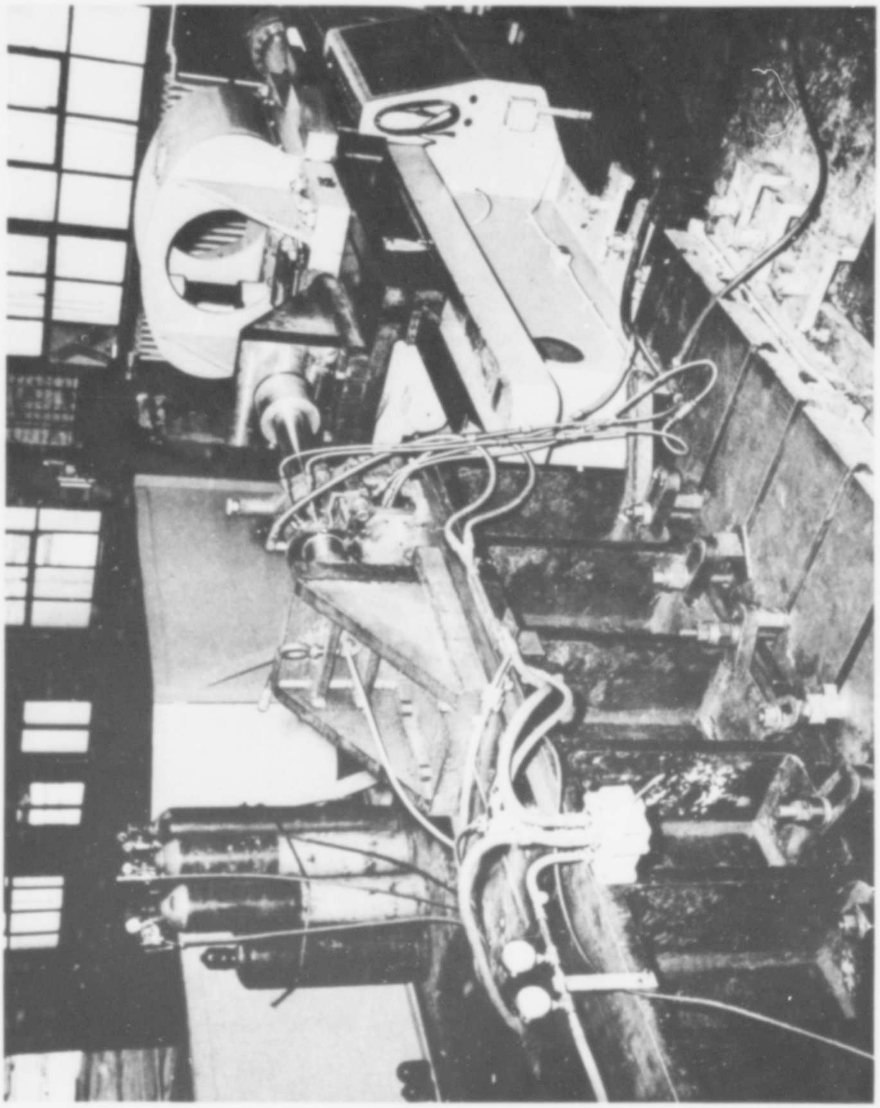
GATLING GUN BARREL INDEXING AND HOLDING BRACKET
Ti-6Al-4V & Ti-4Al-4V

FIGURE 12



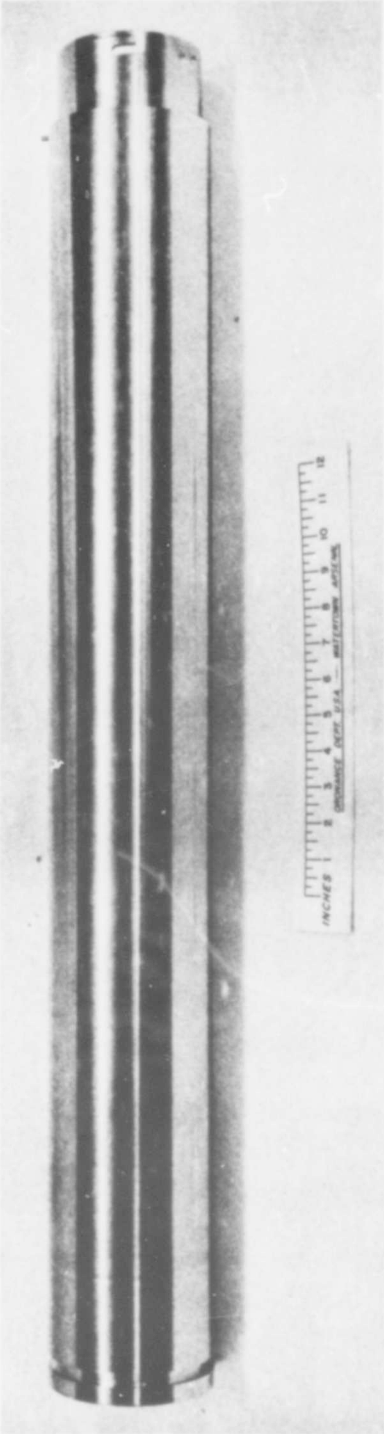
PRESSURE WELDING EQUIPMENT

FIGURE 13



PRESSURE WELDING IN OPERATION

FIGURE 14



PRESSURE WELDED AMMUNITION COMPONENT

FIGURE 15

MECHANICAL PROPERTIES OF PRESSURE WELDED AND INTEGRAL ADAPTER TYPE AMMUNITION COMPONENT

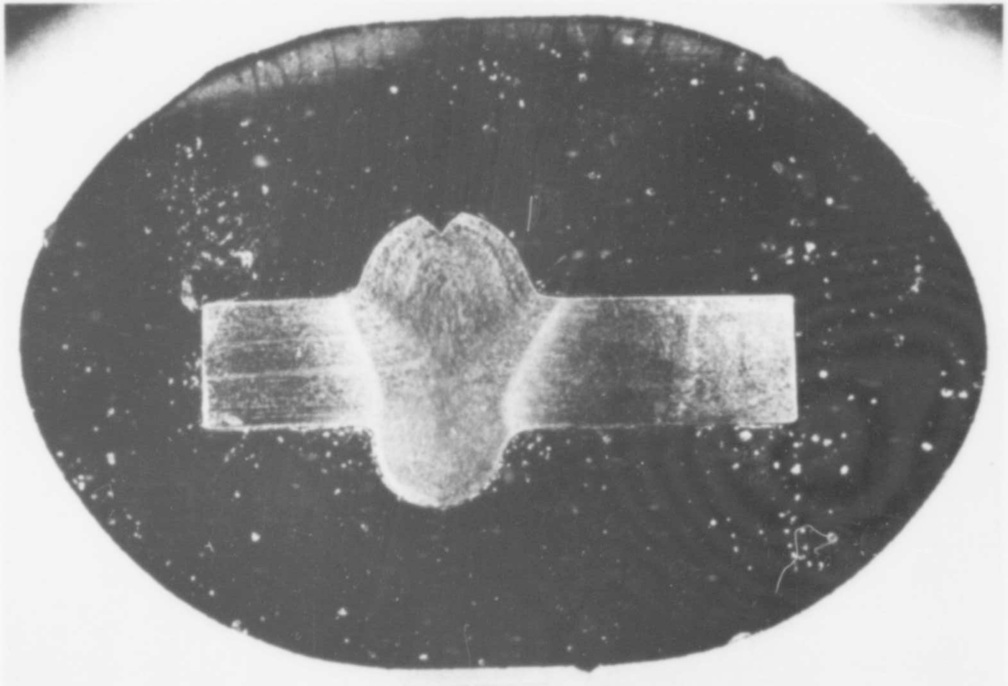
Location	Yield Str. .1% Offset (Psi x 1000)	Elon. (%)	R.A. (%)	V-Notch Charpy Impact at -40°F (ft - lbs)
Cylinder-Adapter	172,750	8.6	21.2	6.7
Cap End	174,000	7.2	27.2	6.1
*Welded Area (Min. Prop.)	145,000	9.0	20.0	9.0

*Increased wall thickness at welded area to allow for slight degradation in mechanical properties resulting from welding operation.

Figure 16

8

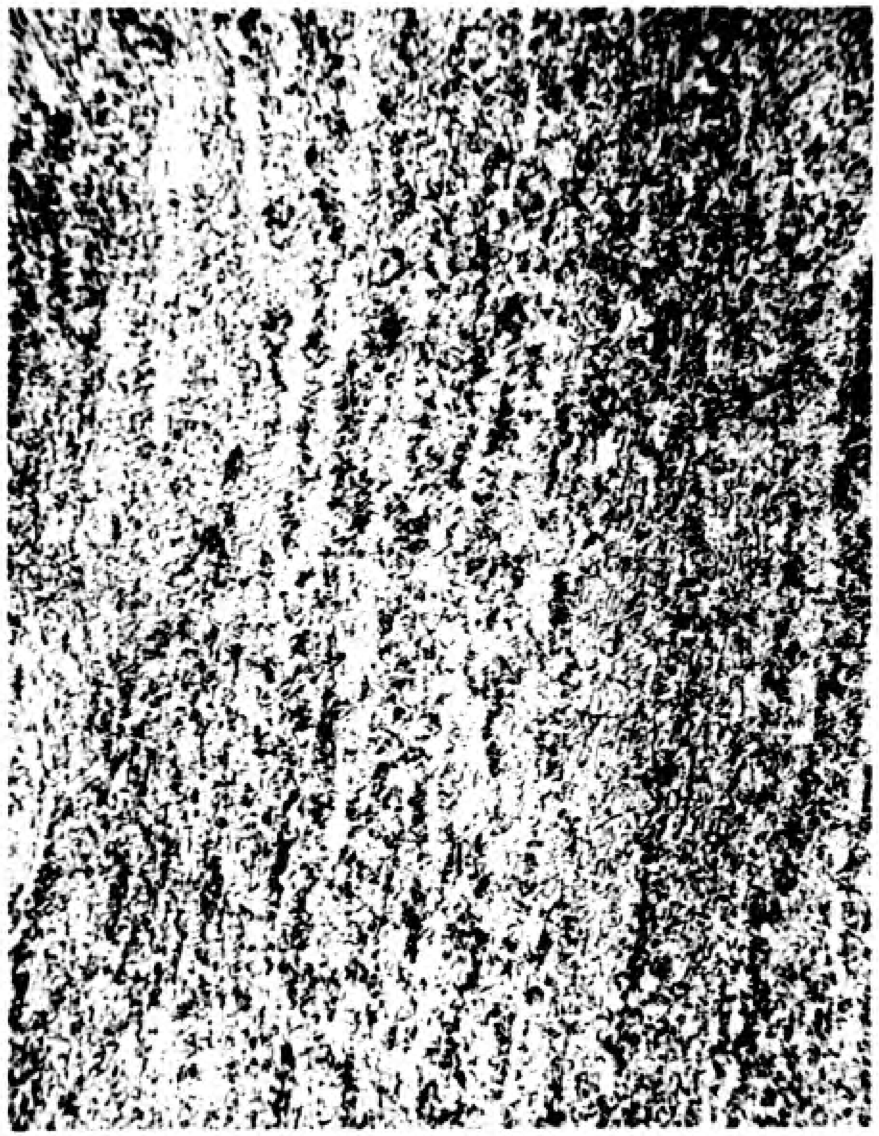
MICROSTRUCTURE OF PRESSURE WELDED JOINT AND BASE MATERIAL



X3

FIGURE 17

MACROSTRUCTURE OF PRESSURE WELDED JOINT



JOINT MATERIAL X100

BASE MATERIAL X100

MICROSTRUCTURE OF PRESSURE WELDED JOINT AND BASE MATERIAL

FIGURE 18

EFFECT OF NOTCH RADIUS ON "V" NOTCH CHARPY IMPACT RESISTANCE

(Ti-6Al-6V-2Sn ALLOY AT 170,000 PSI MINIMUM YIELD STRENGTH)

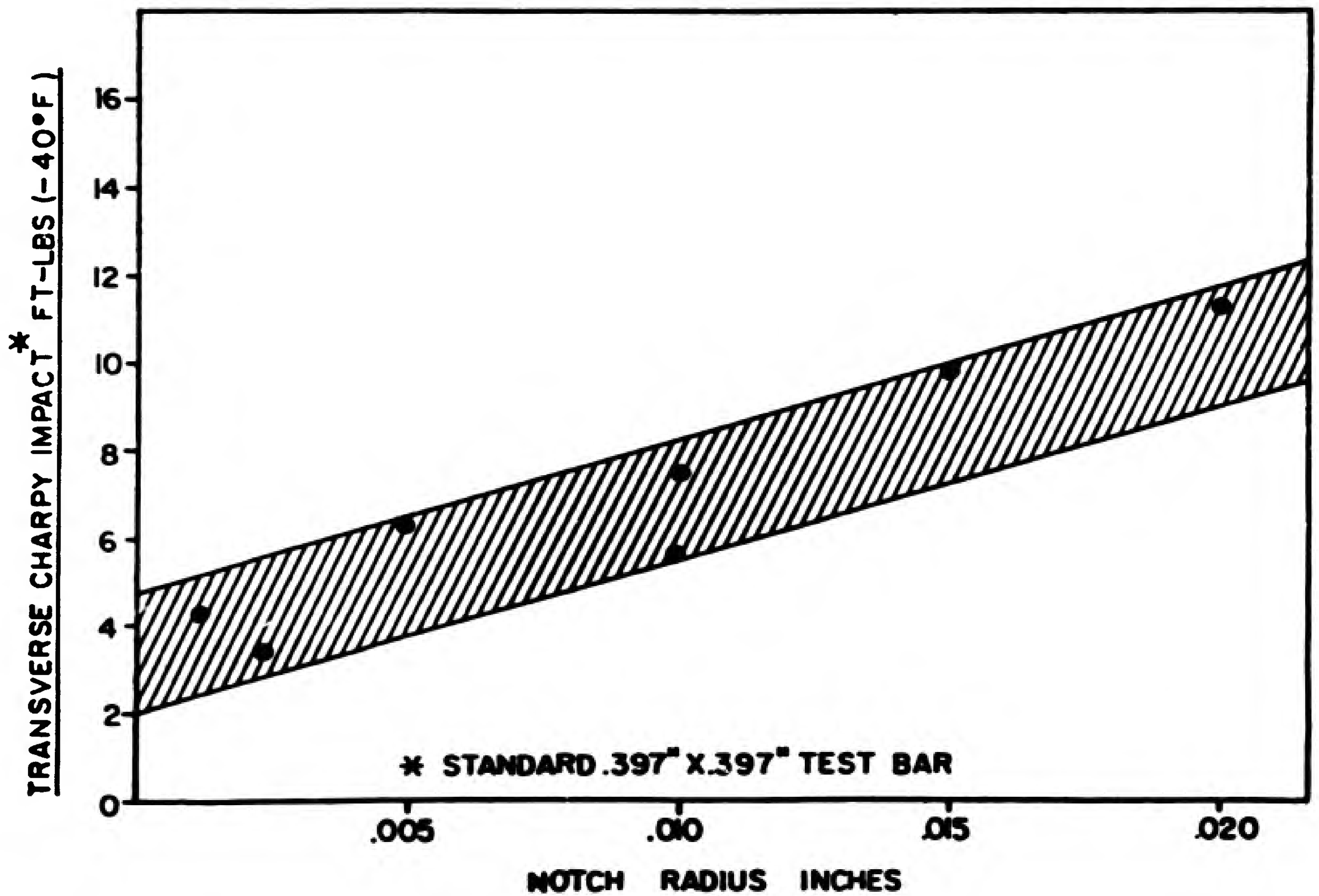
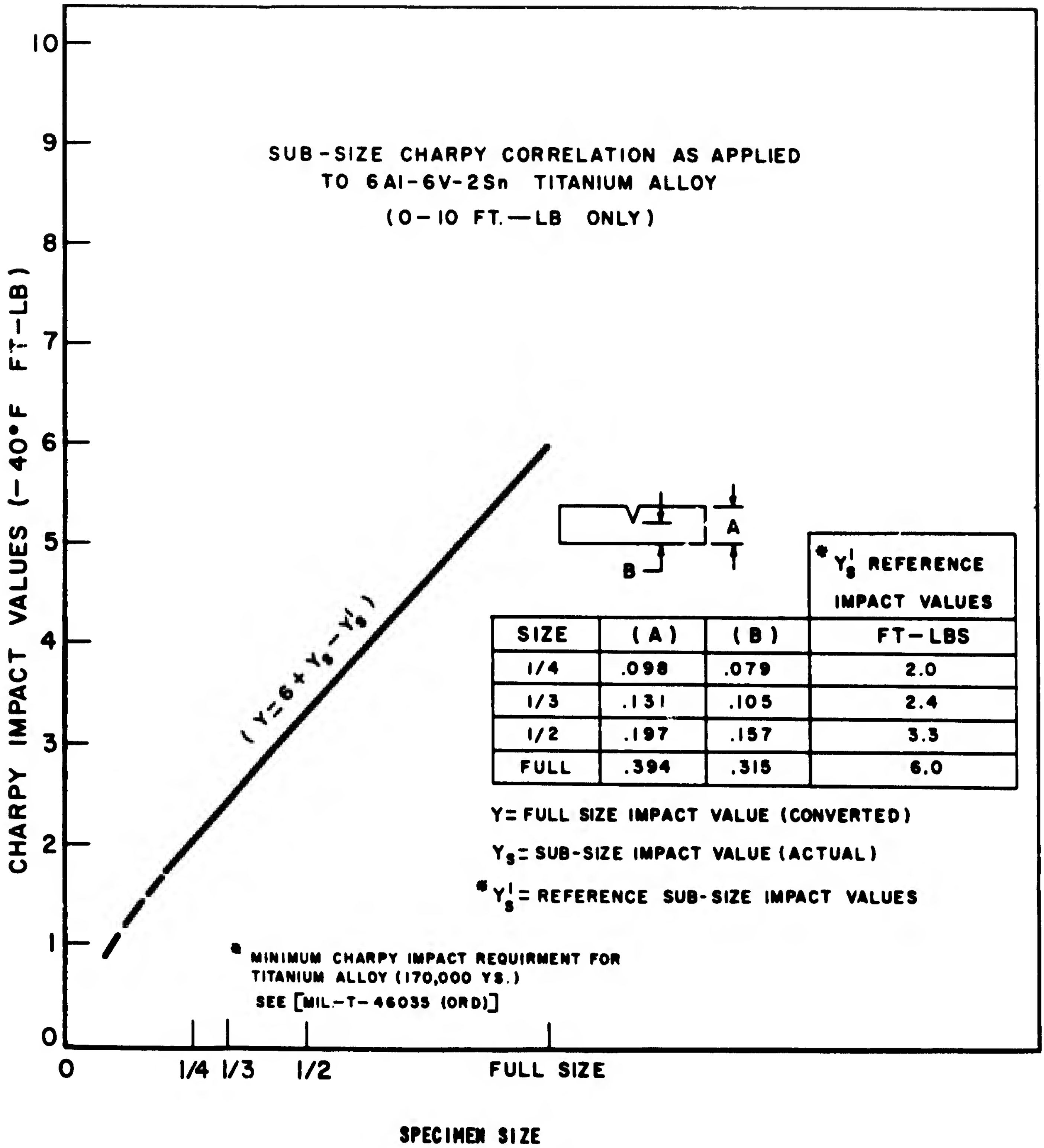


FIGURE 19



EFFECT OF V-NOTCH CHARPY SPECIMEN SIZE ON IMPACT LEVEL

FIGURE 20

COMPRESSION TEST ON THIN WALLED PRESSURE WELDED CYLINDER - 93% WELD EFFICIENCY LOAD - 197,000 LBS

FIGURE 21

COMPRESSION TEST ON THIN WALLED PRESSURE WELDED CYLINDER - 100% WELD EFFICIENCY LOAD - 212,000 LBS

FIGURE 22