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Titanium Alloys For Critical Ordnance Components

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TITANIUM ALLOYS FOR CRITICAL ORDNANCE COMPONENTS

PRODUCERS COORDINATION MEETING
ON
TITANIUM MATERIALS FOR DAVY CROCKETT AND OTHER WEAPON SYSTEMS

HELD AT

WATERTOWN ARSENAL, WATERTOWN 72, MASS.

14 APRIL 1960

AND

FABRICATORS COORDINATION MEETING
ON
TITANIUM MATERIALS FOR DAVY CROCKETT AND OTHER WEAPON SYSTEMS

HELD AT

WATERVLIET ARSENAL, WATERVLIET, NEW YORK

15 APRIL 1960

ORDNANCE CORPS - U. S. ARMY

DISCLAIMER NOTICE

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WATERTOWN ARSENAL
WATERTOWN, MASS.

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WATERTOWN ARSENAL
WATERTOWN, MASS.

PRODUCERS COORDINATION MEETING

TITANIUM MATERIALS FOR DAVY CROCKETT AND OTHER WEAPON SYSTEMS

Agenda
14 April 1960

Fifth Floor Conference Room
Building No. 39 - Room No. 521

Watertown Arsenal
Watertown, Mass.

Time	Subject
0900 - 1000	Meeting of Ordnance Representatives
	Ordnance Weapons Command, Ordnance Ammunition Command, Picatinny Arsenal, Frankford Arsenal, Watertown Arsenal, and Watervliet Arsenal
1030 - 1040	Welcome
	Brig Gen C. E. Rust, Commanding General, Watertown Arsenal
	Program of the Day
	Mr. E. N. Hegge, Project Officer, Davy Crockett, Watertown Arsenal
1040 - 1200	Ordnance Presentations
1040 - 1055	Col R. J. Rastetter, Spec. Asst. to Commanding General, Ordnance Weapons Command Mr. F. Wittber, Asst. Project Officer, Industrial, Davy Crockett Managerial Position of Ordnance Weapons Command - Responsibilities, urgencies, priorities and requirements of readiness of of special weapons.
1055 - 1115	Mr. L. Horowitz, Deputy Director for Davy Crockett, Picatinny Arsenal Mr. M. Bornstein, Staff Assistant for Industrial Transition, Davy Crockett Lightweight, High-Strength Weapon - Timetable of research and development of lightweight, high-strength weapon including phasing in of industrial engineering and initial production.

Agenda (Cont)

14 April 1960

Time	Subject
1115 - 1135	Lt Col G. H. Baxter, Project Officer, Davy Crockett, Watervliet Arsenal Recoilless Weapon Requirements - Yield strength, ductility and toughness, configurations and sizes for metallurgical processing, quantities of material.
1135 - 1155	Mr. E. Roof, Industrial and Maintenance Mission for Davy Crockett, Picatinny Arsenal Special Weapon Ammunition Titanium Materials - Special weapons ammunition titanium materials requirements, industrial engineering projects in metallurgical processing to facilitate production and reduce cost.
1200 - 1230	Demonstration - Bldg. 311 Pressure Welding of High-Strength Titanium
1230 - 1330	Lunch - Watertown Arsenal Cafeteria
1330 - 1500	Engineering Data, Hot-Working and Specifications
1330 - 1410	Mr. R. M. Colton, Watertown Arsenal Laboratories Engineering Data, Specification MIL-T-46038(ORD) Mechanical properties, forging techniques, and heat-treatment cycles as related to alpha-beta type titanium alloys processed to meet the general requirements of specification MIL-T-46038. Emphasis will be made on effects of alloy composition, forging temperature, and reduction ratio in relation to the upset forging test procedure required in this specification.
1410 - 1430	Mr. J. F. Rizzitano, Watertown Arsenal Laboratories Engineering Data, Specification MIL-T-46035(ORD) Mechanical properties, forging techniques, and heat-treatment cycles as related to alpha-beta type titanium alloys processed to meet the general and specific requirements of specification MIL-T-46035. Emphasis will be made on choice of alloy, forging technique and heat-treatment cycles necessary to meet various mechanical and physical requirements stipulated in specification.

Agenda (Cont)

14 April 1960

Time	Subject
1430 - 1445	Mr. E. N. Kinas, Watertown Arsenal Laboratories Hot-Working of Titanium Alloys - Die design and life, lubrication variables, power requirements, temperature control, and forging techniques practiced and evaluated to assure proper component hot-working. Major emphasis will be placed on comparison of these variables on titanium and steel component hot working and of critical areas to be considered.
1445 - 1500	Mr. J. F. Coulter, Watertown Arsenal Laboratories Specifications - Review of specification MIL-T-46038(ORD), Titanium Alloy, Wrought, Rods, Bars, and Billets (For Critical Applications) and MIL-T-46035(ORD), Titanium Alloy, High-Strength, Wrought (For Critical Applications)
1500 - 1530	Mr. E. N. Hegge Summary and Discussion
1530 - 1600	Demonstration - Bldg. 39 Contour Turning and Billet Trepanning of High-Strength Titanium

ORDNANCE CORPS
WATERTOWN ARSENAL
WATERTOWN 72, MASSACHUSETTS

14 April 1960

REPRESENTATIVES OF TITANIUM INDUSTRY AND ORDNANCE CORPS PERSONNEL:

The military specifications being discussed here today reflect, in part, the major advances being made in Ordnance application of alpha-beta type titanium alloy materials. For example, the Ordnance Corps is currently using titanium alloys having a yield strength to density ratio of 850,000, because steel alloys are limited to a ratio of about 700,000 in the sizes required. Industrial procurement of even higher strength titanium alloys having a yield strength to density ratio of 1,000,000 has been scheduled for the Davy Crockett weapons system.

The requirement of critical components for demonstrated toughness and ductility at the specified yield-strength level has led to the development and use of an upset-forging test in the titanium specification for wrought bar and billets. Because forging practice is an important factor affecting solution-treated and aged properties of titanium alloys, it is necessary to follow a prescribed procedure in preparing the upset blank to be used in determination of heat-treatment response. Extensive metallurgical processing of actual Ordnance components have been carried out by means of open- and closed-die forgings and forward and backward extrusions. The mechanical properties realized by these various methods of fabrication successfully met the requirements of the new specifications.

The tabulated data upon which these specifications are based represent several years of cooperative effort between the titanium industry and the Ordnance Corps in development and application of moderately high-strength alloys (120,000 - 159,999 psi yield strength) and an accelerated program during the past two years to employ higher strength alloys (160,000 - 189,999 psi yield strength) for the Davy Crockett program. The data include typical results from approximately 225,000 lbs. of moderate strength and 55,000 lbs. of high-strength titanium alloys evaluated by upset forgings and processed into Ordnance components with many of the latter subsequently subjected to experimental stress-analysis studies as well as ballistic firings.

The establishment of a separate specification for wrought forgings and extrusions indicates, of course, that the Ordnance Corps plans to procure high-strength forgings and extrusions in hot-worked and heat-treated condition as well as continuing to procure bar and billet for subsequent experimental processing of prototype components. Development of this industrial fabrication capability has been an important feature of the Davy Crockett program. Tomorrow at Watervliet Arsenal the data and information given here today are going to be presented to industrial fabricators, and of course, titanium producers who wish to process the material are invited to attend this meeting. Today, however, we wish to report to the titanium industrial producers who have been so cooperative in this development in order that we may arrive at a common understanding of our plans and objectives.

We wish at this time to acknowledge and express our gratitude for the substantial contributions made by the titanium producers in this effort.

C. E. RUST
Brig Gen, USA
Commanding

SECTION B

Agenda and Abstracts - Watervliet Arsenal, Watervliet, New York, 15 April 1960 - Fabricators Coordination Meeting, "Titanium Materials for Davy Crockett and Other Weapon Systems"

Introduction - Col Walter M. Tisdale, Commanding Officer, Watervliet Arsenal

WATERVLIET ARSENAL
WATERVLIET, NEW YORK

PROCESSORS COORDINATION MEETING

TITANIUM MATERIALS FOR DAVY CROCKETT AND OTHER WEAPON SYSTEMS

Agenda
15 April 1960

Third Floor Conference Room
Building No. 10

Watervliet Arsenal
Watervliet, New York

Time	Subject
1000 - 1010	Welcome Colonel W. M. Tisdale, Commanding Officer, Watervliet Arsenal
	Program of the Day Lt Col G. H. Baxter, Project Officer, Davy Crockett, Watervliet Arsenal
1010 - 1145	Ordnance Presentations
1010 - 1025	Colonel R. J. Rastetter, Spec. Asst. to Commanding General, Ordnance Weapons Command Mr. F. Wittber, Assistant Project Officer, Industrial, Davy Crockett Managerial Position of Ordnance Weapons Command - Responsibilities and requirements of readiness of special weapons.
1025 - 1040	Mr. L. Horowitz, Deputy Director for Davy Crockett, Picatinny Arsenal Mr. M. Bornstein, Staff Assistant for Industrial Transition, Davy Crockett Lightweight High-Strength Weapon - Timetable of research and development of lightweight, high-strength weapons including phasing in of industrial engineering and initial production.
1040 - 1055	Lt Col R. Barth, Project Officer, Davy Crockett, Frankford Arsenal Development Background - Development background of Davy Crockett weapon systems including history of material and design.

Agenda (Cont)

15 April 1960

Time	Subject
1055 - 1105	Lt Col G. H. Baxter, Project Officer, Davy Crockett, Watervliet Arsenal Recoilless Weapon Requirements - Yield strength, ductility and toughness; configuration and sizes for metallurgical processing, quantities of material.
1105 - 1120	Mr. E. Roof, Industrial and Maintenance Mission, Davy Crockett, Picatinny Arsenal Special Weapon Ammunition Titanium Materials - Special weapon ammunition titanium material requirements, industrial engineering projects in metallurgical processing to facilitate production and reduce cost.
1120 - 1145	Mr. M. Cohen, Frankford Arsenal Environmental Firing Performance of Davy Crockett Weapons Strength requirements, ballistic testing and environment conditions of recoilless rifles.
1145 - 1245	Lunch - Watervliet Arsenal Cafeteria
1245 - 1425	Engineering Data, Specifications and Fabrication
1245 - 1305	Mr. R. M. Colton, Watertown Arsenal Laboratories Engineering Data - Specification MIL-T-46038(ORD) - Mechanical properties, forging techniques, and heat-treatment cycles as related to alpha-beta type titanium alloys processed to meet the general requirements of specification MIL-T-46038. Emphasis will be made on effects of alloy composition, forging temperature and reduction ratio in relation to the upset forging test procedure required in this specification.
1305 - 1345	Mr. F. J. Rizzitano, Watertown Arsenal Laboratories Engineering Data - Specification MIL-T-46035(ORD) - Mechanical properties, forging techniques, and heat-treatment cycles as related to alpha-beta type titanium alloys processed to meet the general and specific requirements of specification MIL-T-46035. Emphasis will be made on choice of alloy, forging technique and heat-treatment cycles necessary to meet various mechanical and physical requirements stipulated in specification.

Agenda (Cont)

15 April 1960

Time	Subject
1345 - 1400	Mr. J. F. Coulter, Watertown Arsenal Laboratories Specifications - Review of specification MIL-T-46038(ORD), Titanium Alloy, Wrought, Rods, Bars, and Billets (For Critical Applications) and MIL-T-46035(ORD), Titanium Alloy; High-Strength, Wrought (For Critical Applications)
1400 - 1425	Mr. F. Kirwin, Watervliet Arsenal Titanium Machining Experience at Watervliet Arsenal
1425 - 1445	Lt Col G. H. Baxter Summary and Discussion
1445 - 1600	Tour of Arsenal Facilities

ORDNANCE CORPS
WATERVLIET ARSENAL
WATERVLIET, N. Y.

15 April 1960

REPRESENTATIVES OF INDUSTRIAL FABRICATORS AND ORDNANCE CORPS PERSONNEL:

Army Ordnance is greatly interested in the use of high-strength titanium alloys for use where weight is an important factor such as in the current Davy Crockett system. Of the presently available constructional materials which are suitably workable for manufacturing system components, the titanium alloys provide a strength-to-weight ratio sufficiently superior to the other materials to insure the achievement of minimum weight of a system.

A wide range of strength levels in combination with varying degrees of toughness is available in alpha-beta type titanium alloys. Good engineering judgment will dictate the optimum combination of strength and toughness. As with any newly developed material, the background of experience in actual applications is limited. However, this limited experience has been obtained from the application of titanium alloys in systems subjected to some of the most severe operating conditions to which Ordnance materials are subjected, i.e., recoilless guns and ammunition components. This experience has substantiated without question the feasibility of utilizing titanium alloys for many Ordnance applications.

Alloy titanium, which on a strength-weight basis is equivalent to steel at a yield strength of about 300,000 psi, has been selected as the material for both the man-transportable recoilless rifle and the ammunition launching pistons of the Davy Crockett weapons system. This ultimate goal of the lightweight system was realized by virtue of the high strength-to-weight ratio in conjunction with the adequate modulus-to-weight ratio and the suitable toughness available in alpha-beta type titanium alloys. Furthermore, these properties are retained over a wide range of temperatures.

In the thin-walled titanium recoilless gun designed for the Davy Crockett system, the material is subjected to high rates of loading to high strain levels, temperature ranging from -65°F to 500°F, exposure to the erosive effects of hot gases at high velocities, and exposure to the elements. Threads, holes and other such discontinuities are machined into the gun. The diametrical tolerances needed require a high order of dimensional stability and good machineability in the high-strength condition. Surprisingly, protection of the titanium material from the high-temperature propellant gases has been found to be necessary only in the throat and adjacent rearward sections of the nozzle of the gun.

15 April 1960

As pointed out yesterday at a meeting held at Watertown Arsenal with representatives of the titanium industry, development of industrial fabrication capability for the hot-working of alpha-beta types of titanium alloys has been an important feature of the Davy Crockett program. The high-strength titanium alloy materials processing data being presented here today were developed for this program under the technical supervision of the Ordnance Corps ferrous metallurgical research laboratories at Watertown Arsenal, and I would like to express to the Watertown Arsenal Laboratories the appreciation of Frankford Arsenal, Picatinny Arsenal, and Watervliet Arsenal where the various high-strength titanium components were designed and to join in expressing our thanks to the participating industrial organizations.

Perhaps those of you here today who have not had the opportunity to process these materials or to examine as yet the data being furnished are skeptical of the commercial feasibility of processing these high-strength titanium materials. At the outset of the Davy Crockett program two years ago the recoilless rifle and ammunition designers were also skeptical, I can assure you, of the possibility of using materials for critical components with a yield strength-to-density ratio of 1,000,000. Just as the extensive ballistic test data accumulated to date has demonstrated to the designer the excellent behavior of the high-strength titanium material, the processing data being presented here today, I believe, demonstrate that commercial processing of these high-strength titanium materials is virtually assured.

On behalf of Watervliet Arsenal I wish to thank you for the courtesy of attending this meeting and also to thank the various Ordnance Corps representatives for their presentations here today.

/s/ WALTER M. TISDALE
Colonel, Ord Corps
Commanding

SECTION C

Titanium Alloys For Critical Ordnance Components

Military Specification MIL-T-46038(ORD)

Military Specification MIL-T-46035(ORD)

TITANIUM ALLOYS FOR CRITICAL ORDNANCE COMPONENTS

MILITARY SPECIFICATION MIL-T-46038(ORD) WROUGHT, RODS, BARS, AND BILLETS

AND

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

INTRODUCTION

The increasing need for lighter weapons has led to the accelerated development and application of higher strength materials. Wrought titanium alloys have been of particular interest because of their superior strength-to-weight ratio. The requirement for man-transportable components for the Davy Crockett weapons system has been the impetus which forced the exploitation of alpha-beta type titanium alloys having yield strength-to-density ratios of at least 1,000,000 (lbs per sq in/lbs per cubic in).

While a 1,000,000 yield strength-to-density ratio per se is not too difficult to attain, the materials used in critical Ordnance components are also required to have good ductility and notch toughness over a wide range of temperatures. In general, components must perform satisfactorily between -65°F and 160°F, and in some cases, such as for recoilless rifles, at 500°F.

The titanium metallurgical processing data contained in this report was derived from the processing of about 225,000 pounds of material for moderate strength (120,000-159,999 psi yield strength) prototype components and about 55,000 pounds of material for higher strength (160,000 - 189,999 psi yield strength) experimental components.

SUMMARY

The metallurgical data contained in this report demonstrate that several titanium alloys, including Ti-7Al-4V, Ti-6½Al-4V, Ti-6Al-4V, Ti-155A and Ti-6Al-6V-2Sn, meet the general requirements of the new military specifications for the moderate yield strength range (120,000-159,999 psi); and two titanium alloys, Ti-155A and Ti-6Al-6V-2Sn meet the general requirements of the high yield-strength range (160,000-189,999 psi). Only alpha-beta type titanium alloys were investigated and the controls exercised in the selection of alloy composition, forging and processing procedures, and heat-treatment cycles are discussed.

WATERTOWN ARSENAL PURCHASE DESCRIPTION WA-PD-76C(1)

The two military specifications of this report, MIL-T-46035(ORD) and MIL-T-46038(ORD), supersede Watertown Arsenal Purchase Description WA-PD-76C(1). This purchase description, used for the procurement of titanium alloys for the past several years, was frequently revised as titanium technology advanced. The large amount of metallurgical data accumulated to date and the need to incorporate the higher strength (greater than 160,000 psi yield strength) capabilities of new alpha-beta type titanium alloys warranted the preparation of formal military specifications at this time.

MILITARY SPECIFICATIONS MIL-T-46035(ORD) AND MIL-T-46038(ORD)

Basically, MIL-T-46038(ORD) covers the procurement of wrought rods, bars, and billets in the mill form, and MIL-T-46035(ORD) covers the procurement of hot-worked forgings and extrusions. It is evident that the former specification is utilized either for the procurement of material for subsequent conversion into configurations covered by the latter specification, or for general procurement of mill products for specialized applications. The reason for preparing two specifications in lieu of one (purchase description) is due to the increasing complexity of material requirements as related to configuration and mechanical properties.

A question which immediately arises is that since forgings and extrusions are procured in accordance with certain mechanical-property requirements stipulated in one specification (MIL-T-46035), why does this same specification require that the mill products used in the conversion process meet specified mechanical properties stipulated under a second specification (MIL-T-46038)? The answer is very brief. Watertown Arsenal Laboratories experience has shown that the requirements specified in MIL-T-46035 can only be met by utilizing mill products capable of meeting the equivalent yield-strength range requirements stipulated in MIL-T-46038. Thus, in specification MIL-T-46038 the impact requirement serves as a method of quality control as well as a measure of toughness.

It should be noted that both specifications require that the density or the alloy supplied shall not exceed 4.70 $^{GM}/cm^3$. This step is necessary in order to maintain a narrow band of strength-density ratios for a particular strength range. All alloys designated in the data presented meet this density requirement. In some cases an elevated-temperature requirement is specified (See Par. 4.5.2.2.1 of MIL-T-46035). Again this is necessary where the components are subjected to special performance cycles.

Military specification MIL-T-46038(ORD), Titanium Alloy, Wrought, Rods, Bars and Billets, is discussed in Section A which follows, while MIL-T-46035(ORD), Titanium Alloy, High-Strength, Wrought, is discussed in Section B. Copies of these specifications are attached to this report.

SECTION A - MILITARY SPECIFICATION MIL-T-46038(ORD)

INDUSTRIAL ALLOY DEVELOPMENT

The distinguishing feature and basic requirement of MIL-T-46038 is centered around the upset-forging test utilized for mechanical-property evaluation (See Figure 4). The actual test procedure is outlined in the specification, but a brief description is presented here for increased clarity. Essentially, the test consists of upsetting a billet axially at a stipulated temperature from a 5-inch height to the prescribed thickness shown in the specification (See Table II, Page 6, MIL-T-46038). The test specimens are taken from locations which can be best described as tangential to a series of concentric circles within the upset disc (See Page 7, MIL-T-46038). For small diameter bars or rods the tests are longitudinal (See Par. 4.5.2.1.1, MIL-T-46038), and for large diameter billets (See Par. 4.5.2.1.4) the bars are again tangential; however, the sampling procedure is slightly modified. In this case a 2-inch disc is cut from the end of the billet, quartered and sectioned into 4-inch high rectangular-shaped plates, and upset parallel to the 4 inch dimension at the prescribed temperature and to the prescribed thickness.

The four sheets of tabulated results designated under Table I contain test data obtained from material purchased to requirements similar to those stipulated in specification MIL-T-46038. However, it should be noted that whereas the original billet height before upset is 4 inches for the test data shown in these tables, the new requirements in MIL-T-46038 designate a 5-inch billet height. This modification increases the amount of hot work during upset and correspondingly increases the ease in meeting the desired mechanical properties.

Basically, the table is divided into two sections, one covering yield strength ranges of 120,000-159,999 psi and the second covering yield-strength ranges of 160,000-189,999 psi. The range is designated at the top of each page. In all cases data covering only alpha-beta type alloys is presented. The particular alloy and its actual composition is shown in columns C through L; the alloy heat number is shown in column B; and the producer which is shown in column A is indicated by an alphabetical code, except for proprietary alloys. Column M shows the facility conducting the chemical analysis evaluation ("Gov't" for Government testing and "Ind" for industrial testing by the producer designated under column A). The size of the billets obtained and the weights of each size are shown in columns N and O, respectively. The upset forging procedure is shown in column P, and the heat treatment and type of quench are shown in columns Q, R, and S. The mechanical property results are tabulated in columns T, U, V, W, and X, and the facility performing the mechanical-property testing is designated under column Y.

YIELD-STRENGTH REQUIREMENT 120,000 - 159,999 PSI

At this point is is desirable to more closely evaluate the alloys, processing procedures, and test results obtained, which correspond to the designated yield-strength range requirements.

The data tabulated in sheets 1 and 2 of Table I represent approximately 225,000 lbs. of titanium purchased by Watertown Arsenal over the last three years. It should be noted that approximately 90% of all the material tested in Table I, sheets 1 and 2 meet all of the requirements specified in MIL-T-46038. Improvement of this figure to approximately 100% will result from the use of the 5-inch high test billet and improved processing procedures and heat treatments.

Only the nominal analysis of each alloy is listed. The exact analysis is in accordance with commercial tolerances. It should be noted under Par. 3.1 of MIL-T-46038 that only maximum interstitial contents are specified, and that the actual compositions are left up to the discretion of the producer.

In general, specific alloys, forging procedures and heat-treatment cycles are related to the individual strength-range requirements. The following chart summarizes the recommended alloys and corresponding processing procedures necessary to meet those requirements. The data in this chart is taken directly from the tabulated results shown in Table I, Sheets 1 and 2.

CHART I

Strength Range .1% Offset	Alloy	Upset Temp. °F	Thickness (In.)	Heat Treatment Sol. °F	Age °F
120-129,999	Ti-6Al-4V	1750 - WQ	2	None	1300-4hr-AC
"	Ti-6½Al-4V	1750 - WQ	"	"	"
"	Ti-7Al-4V	1775 - WQ	"	"	1350-4hr-AC
130-139,999	Ti-6Al-4V	1750 - WQ	1½	1700-1hr-WQ	1200-4hr-AC
"	Ti-6½Al-4V	1750 - WQ	"	1700-1hr-WQ	1200-4hr-AC
"	Ti-7Al-4V	1775 - WQ	"	1725-1hr-WQ	1250-4hr-AC
"	Ti-155A	1675 - WQ	"	1650-1hr-WQ	1300-4hr-AC
"	Ti-6Al-6V-2Sn	1675 - WQ	"	1630-1hr-WQ	1300-4hr-AC
140-149,999	Ti-6½Al-4V	1700 - WQ	1½	1700-1hr-WQ	1100-1150-4hr-AC
"	Ti-7Al-4V	1725 - WQ	"	1725-1hr-WQ	1150-4hr-AC
"	Ti-155A	1675 - WQ	"	1650-1hr-WQ	1250-4hr-AC
"	Ti-6Al-6V-2Sn	1675 - WQ	"	1630-1hr-WQ	1250-4hr-AC
150-159,999	Ti-7Al-4V	1725 - WQ	1	1725-1hr-WQ	1100-4hr-AC
"	Ti-155A	1675 - WQ	"	1650-1hr-WQ	1200-4hr-AC
"	Ti-6Al-6V-2Sn	1675 - WQ	"	1630-1hr-WQ	1200-4hr-AC

YIELD-STRENGTH REQUIREMENT 160,000 - 189,999 PSI

It is quite understandable that close alloying and processing control must be held in order to meet the high-strength requirements designated under this section. The data tabulated in sheets 3 and 4 of Table I represent the testing and evaluation of approximately 30,000 lbs. of Ti-6Al-6V-2Sn and 25,000 lbs. of Ti-155A. It should be noted that approximately 75% of the material tested in Table I, sheets 3 and 4 meets all of the requirements specified in MIL-T-46038. It should be noted that this 75% acceptance figure includes material which was not of the optimum chemical analysis and/or was experimentally processed and heat treated to establish optimum procedures. This acceptance rate can approach 100% if the optimum chemical analysis, processing procedures and heat treatments are utilized as recommended in this report. In addition, the use of the new 5-inch high test billet will greatly aid in establishing an all acceptable material.

The nominal analysis and the exact analysis of all heats of the Ti-6Al-6V-2Sn alloy are shown because of the close control required on this material for proper mechanical-property response. Only the nominal analysis is presented for the Ti-155A alloy and more exact information can be obtained from Titanium Metals Corporation of America.

ALLOY COMPOSITION

The effect of high N_2 and O_2 contents on mechanical properties is convincingly shown in lines 37-42 of Table I, sheet 4. Although the strength is markedly increased, there is a decided drop in ductility and toughness to levels below that of the specification requirement. By lowering these contents to those shown in lines 5-8 of Table I, sheet 4, the strength is slightly lowered, but the ductility and toughness are raised to acceptable levels. The recommended analysis for the Ti-6Al-6V-2Sn alloy is presented below:

Al - 5.2-5.8%
V - 5.2-5.8%
Sn - 1.7-2.3%
Fe - 0.5-0.9%
Cu - 0.5-0.9%
C - .05% Max.
O - .12-.19% Max.
H - .012% Max.
N - .025 - .05% Max.

Although suggested ranges are shown above, the specification requires the maintaining of only maximum interstitial contents with no range specified for substitutional alloying elements. The nominal analysis and range is left up to the discretion of the producer.

MELTING PROCEDURE

The standard melting procedure currently employed for such alloys as Ti-6Al-4V is applicable to the Ti-6Al-6V-2Sn alloy. However, master alloy selection is very critical in order to obtain homogeniety in the final melt. More detailed information can be obtained from the master alloy suppliers.

FORGING TECHNIQUES

The most important aspects in obtaining high-strength properties with good ductility and toughness for a particular alloy composition are forging temperature and amount of hot working at this temperature. It has been shown (See Figure 5) that for the Ti-6Al-6V-2Sn alloy a minimum of 50% change in cross-sectional area at temperatures below that of the beta-transus following beta-exposure is necessary in order to avoid an embrittled material. Consequently, the specified upset procedure always incorporates temperatures at least 75°F below the beta-transus temperature and hot-working reductions in excess of 50%. In addition, the specification requires that all rod, bar, and billet supplied must exhibit a minimum elongation of 8% when evaluated in the original mill product prior to upsetting. This requires finishing temperatures well below that of the beta-transus, and this assures a ductile material. The following chart elaborates on recommended forging temperatures and required maximum thicknesses and heat-treatment procedures for upset tests. The data in this chart is taken directly from the tabulated results shown in Table I, sheets 3 and 4.

CHART II

Strength Range .1% Offset	Alloy	Upset Temp. °F	Thickness (In.)	Heat Treatment Sol. °F	Heat Treatment Age °F
160-169,999	Ti-155A	1675 - WQ	1	1650-1hr-WQ	1150-4hr-AC
"	Ti-6Al-6V-2Sn	1675 - WQ	1	1630-1hr-WQ	1150-4hr-AC
170-179,999	Ti-155A	1675 - WQ	3/4	1650-1hr-WQ	1100-4hr-AC
"	Ti-6Al-6V-2Sn	1650 - WQ	3/4	1630-1hr-WQ	1100-4hr-AC
180-189,999	Ti-6Al-6V-2Sn	1650 - WQ	3/4	1630-1hr-WQ	1050-4hr-AC

HEAT TREATMENT

In addition to practicing the proper forging techniques one must use the proper heat-treatment cycle in order to assure obtaining adequate mechanical properties. Generally, the solution temperature should be at least 100°F below that of the beta-transus, and the aging temperature is bracketed by the 1000-1150°F range. Recommended cycles are shown in the above table and can be correlated with results obtained in Table I, sheets 3 and 4.

In general, raising the solution temperature while maintaining the same aging temperature increases strength but decreases ductility and toughness. Conversely, raising the aging temperature while maintaining the same solution temperature decreases the strength but increases the ductility and toughness. Consequently, it is quite obvious that the proper combination of solution and aging temperatures must be exercised.

SECTION SIZE

The section size of the hot-worked or rough-machined component is important with respect to both the amount of hot working imparted and the heat-treatment response. The effects of both these variables are shown in Table I, and the recommended procedures are shown in Chart II.

HIGH-TEMPERATURE PROPERTIES

In specific Ordnance application minimum elevated mechanical properties are required (See Par. 4.5.2.2.1, MIL-T-46035). Only the Ti-6Al-6V-2Sn alloy is capable of meeting this requirement while maintaining its high yield strength (170,000 psi min.) at room temperatures. Elevated temperature properties for three titanium alloys are shown in Figures 1, 2, and 3.

SECTION B - MILITARY SPECIFICATION MIL-T-46035(ORD)

INDUSTRIAL HOT-WORKING DEVELOPMENT

The basic purpose of MIL-T-46035 is to provide a specification for the procurement of backward and forward extrusions and closed- and open-die forgings to designated yield-strength levels for medium- and high-strength titanium alloys used in critical Ordnance applications. In general, testing will be performed on transverse specimens unless the use of such is precluded. Such specimens will be machined from rings, in the case of extrusions, and from rings or discs in the case of forgings. A sampling plan will usually be designated for each particular hot-worked configuration; however, the above general description will be applicable in most cases. Typical forgings and extrusions are shown in Figures 6 through 15, and the corresponding processing procedures and mechanical-property results are shown in Table II, sheets 1, 2, 3, and 4. The data presented in this table were obtained from material processed to meet the requirements specified in MIL-T-46035.

Basically the table is divided into two sections; one covering yield strength ranges of 120,000-169,999 psi and the second covering yield-strength ranges of 160,000-189,999 psi. The actual yield-strength range required is designated under column L in each sheet. In all cases only data on alpha-beta type alloys is presented. Column A shows the hot-working facility which processed the particular part, and is copied alphabetically except where processing was accomplished at Watertown Arsenal; Column B shows the heat number of the titanium alloy utilized and the producer of the alloy. The producers are coded alphabetically except in the case where proprietary alloys are employed. A direct alphabetical correlation exists between the producers shown in Table I and Table II. Consequently, the test results obtained from a specific heat of billet or bar material in Table I can be directly compared with the test results obtained from the forgings and extrusions processed from the same heat of material in Table II. Column D shows the part number of the item processed, and a photograph of each part identified by number is shown in Figures 6 through 15. Column

E and F show respectively the billet diameter and weight of each individually processed component. Column G shows the forging temperature and cooling media, and the typical as-processed section size is shown in column H. Column I and J show the heat treatments utilized on the as-processed or rough-machined components. Columns M, N, O, P, and Q tabulate the mechanical properties obtained from the heat-treated components.

YIELD-STRENGTH REQUIREMENT 120,000 - 169,999 PSI

As with the previous specification it now becomes desirable to more closely evaluate the alloys, processing procedures and test results obtained corresponding to the designated yield-strength range requirements.

The data tabulated in sheets 1 and 2 of Table II represent approximately 225,000 lbs. of titanium processed by Watertown Arsenal over the last three years. It should be noted that over 90% of all the material tested in Table II, sheets 1 and 2 meet all of the requirements specified in MIL-T-46035. This percentage would closely approach 100% if data on experimental components were not included in the table. Only the nominal analysis of each alloy is listed, as the exact analysis is either in accordance with current commercial tolerances or is shown in Table I, sheets 1 through 4. In general, specific alloys, forging procedures, and heat-treatment cycles are related to the individual strength-range requirements. The data in the following chart showing these effects is taken directly from the tabulated results shown in Table II, sheets 1 and 2.

CHART III

Strength Range .1% Offset	Alloy	Forg. or Ext. Temp. (°F)	Heat Treatment Sol. °F	Heat Treatment Age °F
120-129,999	Ti-6Al-4V	1675-1775 - WQ	None	1300-4hr-AC
"	Ti-6½Al-4V	1675-1800 - WQ	None	1300-4hr-AC
"	Ti-7Al-4V	1675-1800 - WQ	None	1350-4hr-AC
130-139,999	Ti-6Al-4V	1675-1775 - WQ	1700-1hr-WQ	1250-4hr-AC
"	Ti-6½Al-4V	1675-1800 - WQ	1700-1hr-WQ	"
"	Ti-7Al-4V	1675-1800 - WQ	1725-1hr-WQ	"
"	Ti-155A	1650-1725 - WQ	None	1300-4hr-AC
"	Ti-6Al-6V-2Sn	1650-1700 - WQ	None	1300-4hr-AC
140-149,999	Ti-6½Al-4V	1675-1800 - WQ	1700-1hr-WQ	1150-1200-4hr-AC
"	Ti-7Al-4V	1675-1800 - WQ	1725-1hr-WQ	1200-4hr-AC
"	Ti-155A	1650-1725 - WQ	1650-1hr-WQ	1250-4hr-AC
"	Ti-6Al-6V-2Sn	1625-1700 - WQ	1630-1hr-WQ	1250-4hr-AC

CHART III (Cont)

Strength Range .1% Offset	Alloy	Forg. or Ext. Temp. (°F)	Heat Treatment Sol. °F	Age °F
150-159,999	Ti-6½Al-4V	1675-1800 - WQ	1700-1hr-WQ	1100-4hr-AC
"	Ti-7Al-4V	1675-1800 - WQ	1725-1hr-WQ	1150-4hr-AC
"	Ti-155A	1650-1725 - WQ	1650-1hr-WQ	1200-4hr-AC
"	Ti-6Al-6V-2Sn	1625-1700 - WQ	1630-1hr-WQ	1200-1250-4hr-AC
160-169,999	Ti-7Al-4V	1675-1800 - WQ	1700-1hr-WQ	1050-1100-4hr-AC
"	Ti-155A	1650-1725 - WQ	1650-1hr-WQ	1150-4hr-AC
"	Ti-6Al-4V-2Sn	1625-1700 - WQ	1630-1hr-WQ	1150-1200-4hr-AC

YIELD-STRENGTH REQUIREMENT 160,000 - 189,999 PSI

As pointed out under MIL-T-46038, close processing control must be practiced in order to meet the high-strength requirements designated under this section. The data tabulated in pages 3 and 4 of Table II represent the processing and testing of approximately 30,000 lbs. of Ti-6Al-6V-2Sn and 25,000 lbs. of Ti-155A. It should be noted that approximately 95% of the components processed and tested in Table II, sheets 3 and 4 meet all of the requirements specified in MIL-T-46035.

The exact analysis of the Ti-6Al-6V-2Sn alloy utilized in Table II can be obtained by referring to the same heat number listed in Table I.

FORGING AND HEAT-TREATMENT TECHNIQUES

As mentioned under MIL-T-46038 the most important aspects in obtaining high-strength properties with good ductility and toughness for a particular alloy composition are hot-working temperature and amount of working at this temperature. The following chart briefly summarizes the optimum alloy, forging or extrusion temperatures, heat-treatment cycle for obtaining specified yield strength ranges as designated in MIL-T-46035. The data in this chart is taken directly from the tabulated results shown in Table II, sheets 3 and 4.

CHART IV

Strength Range .1% Offset	Alloy	Forg. or Ext. Temp. °F	Heat Treatment Sol. °F	Age °F
160-169,999	Ti-7Al-4V	1675-1800 - WQ	1700-1hr-WQ	1050-1100-4hr-AC
"	Ti-155A	1650-1725 - WQ	1650-1hr-WQ	1150-4hr-AC
"	Ti-6Al-6V-2Sn	1625-1700 - WQ	1630-1hr-WQ	1150-1200-4hr-AC
170-179,999	Ti-155A	1650-1725 - WQ	1650-1hr-WQ	1050-1100-4hr-AC
"	Ti-6Al-6V-2Sn	1625-1675 - WQ	1630-1hr-WQ	1100-4hr-AC
180-189,999	Ti-6Al-6V-2Sn	1625-1675 - WQ	1630-1hr-WQ	1050-4hr-AC

DISCUSSION

As with requirements for MIL-T-46038 in order to obtain the desired yield-strength levels the proper combination of alloy selection, forging, or extrusion temperatures, hot-working reduction, and heat-treatment cycle must be obtained.

As shown in Table II, column G, practically all components are immediately water quenched following forging or extrusion. Where such water quenching is possible, it is beneficial to utilize this operation. However, if forging temperatures are below that of the beta-transus, air cooling may be substituted if water quenching is impractical. If forging temperatures are above that of the beta-transus, water quenching is essential to avoid excessive grain growth and subsequent embrittlement. The effect of water quenching beta-process forgings is shown on lines 54 and 55, Table II, sheet 1.

FORWARD EXTRUSIONS

For forward extrusions having room temperature, yield-strength requirements of 170,000 psi minimum and no elevated temperature requirements either Ti-155A or Ti-6Al-6V-2Sn can be utilized. Examples are shown in lines 1 through 62 of Table II, sheet 3, and Table II, sheet 4, lines 12 through 15 and Figures 6 and 7 for part numbers 605 and 606. It should be noted that for the Ti-6Al-6V-2Sn alloy the maximum permissible extrusion temperature is 1675°F (See Table II, sheet 3, lines 1 through 29). Although acceptable properties are occasionally obtained at higher temperatures (Table II, sheet 3, lines 30 through 44) uniformity of results are not obtained above the 1675°F. For the Ti-155A alloy extrusion temperatures up to 1725°F are permissible for both the 605 and 606 parts and slightly higher temperatures can be used if absolutely necessary (See Table II, sheet 3, lines 45 through 62 and sheet 4, lines 12 through 15). Acceptable properties can be obtained from either alloy utilizing the forging temperatures and heat treatments shown in Chart IV for the 170,000-189,999 yield-strength range. In both alloys extrusion ratios of 7 to 1 to 10 to 1 give acceptable results.

For forward extrusions having room temperature yield-strength requirements of 170,000 psi minimum and elevated-temperature requirements only the Ti-6Al-6V-2Sn alloy can be used. An example is shown on Table II, sheet 4, lines 16 through 20 and Figure 6. Although satisfactory properties were obtained at an extrusion temperature of 1750°F for this part, it is felt that a maximum temperature of 1675°F should be established to allow for the variance in alloy composition and beta-transus temperature. An extrusion ratio of 7 to 1 is again sufficient and the heat-treatment cycle indicated in Chart IV, for the 170,000-189,999 yield-strength range is recommended.

BACKWARD EXTRUSIONS

For backward extrusions having room temperature yield-strength requirements of 160,000 psi minimum and no elevated temperature the Ti-155A, Ti-6Al-6V-2Sn and Ti-7Al-4V alloy can be utilized. Typical examples are shown in Table II, sheet 4, lines 45 through 62 and Figure 8. Extrusion temperature ranges and recommended heat-treatment cycles are shown in Chart IV. Reduction ratios of 5 to 1 are adequate to meet the 160,000-169,999 yield-strength requirement when processed as recommended above.

CLOSED-DIE FORGINGS

For closed-die forgings having room temperature yield-strength requirements of 170,000 psi minimum and having no elevated temperature properties either Ti-155A or Ti-6Al-6V-2Sn can be used. A typical example is shown in Table II, sheet 5, lines 1 through 11 and 41 and 42, and Figures 7 and 9. The forging temperatures and heat-treatment cycles shown on these lines are considered adequate to obtain the desired mechanical-property range. A hot-working reduction of 50% is also considered adequate for obtaining the desired mechanical properties.

For closed-die forgings having room temperature yield-strength requirements of 170,000 psi minimum and elevated temperature requirements, only the Ti-6Al-6V-2Sn alloy is usable. A typical example is shown in Table II, sheet 4, lines 36 through 40 and Figure 10. The forging temperatures and heat-treatment cycles shown on these lines are considered adequate to obtain the desired mechanical-property range. A hot-working reduction of 50% is also considered adequate.

EXPANDED FORWARD EXTRUSIONS

For expanded forward extrusions having a room temperature yield-strength requirement of 170,000 psi minimum and elevated temperature requirements only the Ti-6Al-6V-2Sn alloy is usable. A typical example is shown in Table II, sheet 4, lines 20 through 35 and Figure 10. The forging temperatures and heat-treatment cycles shown on these lines are considered adequate to obtain the desired mechanical-property range. A hot-working reduction of 50% is also considered adequate.

OPEN-DIE FORGINGS

For open-die forgings having a room temperature yield-strength requirement of 170,000 psi minimum and elevated temperature requirements only the Ti-6Al-6V-2Sn can be used.

ELEVATED TEMPERATURE REQUIREMENTS

As mentioned previously certain components require specific elevated temperature minimum yield-strength properties because of special applications. As stated in MIL-T-46038 a minimum .1% offset yield strength of 130,000 psi is required after 1/2 hour exposure. As shown in Figure 1, the Ti-6Al-6V-2Sn alloy meets this requirement; however, the Ti-155A and Ti-6Al-4V alloys, as shown in Figures 2 and 3 fall short of this requirement.

SUMMARY

The mechanical properties required in MIL-T-46035 can be attained through proper selection of alloy composition, forging and processing procedure, and heat-treatment cycle as discussed throughout this report.

ACKNOWLEDGEMENT

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11 April 1960

TYPICAL METALLURGICAL PROPERTIES OF ALPHA-BETA TYPE TITANIUM ALLOYS

—IN ACCORDANCE WITH—

MILITARY SPECIFICATION MIL-T-46038 (ORD)

(WROUGHT, RODS, BARS AND BILLETS)

TABLE I

WATERTOWN ARSENAL LABORATORIES

DATE: 30 MARCH 1960

SHEET 1 OF 4

YIELD STRENGTH RANGE 120,000-159,999 P.S.I. (TANGENTIAL TEST PROPERTIES)

			COMPOSITION %											BILLET		FORGING & HEAT TREAT			
	PRODUCER	HEAT	NOMINAL	AL	V	Sn	Cu	Fe	C	O	H	N	TESTED BY	DIAMETER INCHES	WEIGHT LBS	(°F) UPSET FORGING	(°F) SOLUTION TREATMENT	(°F) AGING TREATMENT	CONDITION
1	D	69	6.5Al-4V	—	—	—	—	—	—	—	—	—	—	[illegible]	400	LONG TEST	1750-1½HR-WQ	1050-3HR-AC	HEAT TREATED
2	D	"	"	—	—	—	—	—	—	—	—	—	—	"	"	"	"	"	"
3	D	"	"	—	—	—	—	—	—	—	—	—	—	"	"	"	"	"	"
4	D	"	"	—	—	—	—	—	—	—	—	—	—	"	"	"	"	"	"
5																			
6																			
7	D	37	6Al-6V-2Sn	5.80	5.50	2.10	0.62	0.84	0.03	0.18	—	0.03	WD	8¼	2000	1875-4" TO [illegible]	1650-1½HR-WQ	1250-4HR-AC	HEAT TREATED
8	D	"	"	—	—	—	—	—	—	—	—	—	—	"	"	"	"	"	"
9																			
10																			
11	D	72	6.5Al-4V	—	—	—	—	—	—	—	—	—	—	5	420	1675-4" TO [illegible]	1650-½HR-WQ	900-16HR-AC	HEAT TREATED
12	D	"	"	—	—	—	—	—	—	—	—	—	—	"	"	"	"	"	"
13	D	69	"	—	—	—	—	—	—	—	—	—	—	2	328	"	"	"	"
14	D	"	"	—	—	—	—	—	—	—	—	—	—	"	"	"	"	"	"
15	D	71	"	—	—	—	—	—	—	—	—	—	—	8½	1000	1700-4" TO [illegible]	"	"	"
16	D	"	"	—	—	—	—	—	—	—	—	—	—	"	"	"	"	"	"
17	D	75	"	—	—	—	—	—	—	—	—	—	—	"	"	"	"	"	"
18	D	"	"	—	—	—	—	—	—	—	—	—	—	"	"	"	"	"	"
19	D	73	"	—	—	—	—	—	—	—	—	—	—	5	444	1650-4" TO [illegible]	"	"	"
20	D	"	"	—	—	—	—	—	—	—	—	—	—	"	"	"	"	"	"
21																			
22																			
23	E	47	6.5Al-4V	—	—	—	—	—	—	—	—	—	—	8½	1000	1700-4" TO [illegible]	1700-2HR-WQ	1100-4HR-AC	HEAT TREATED
24	E	"	"	—	—	—	—	—	—	—	—	—	—	"	"	"	"	"	"
25	E	"	"	—	—	—	—	—	—	—	—	—	—	"	"	"	"	"	"
26	E	"	"	—	—	—	—	—	—	—	—	—	—	"	"	"	"	"	"
27	E	40	"	—	—	—	—	—	—	—	—	—	—	4¼	500	"	"	"	"
28	E	"	"	—	—	—	—	—	—	—	—	—	—	"	"	"	"	"	"
29	E	39	"	—	—	—	—	—	—	—	—	—	—	2½	"	"	"	"	"
30	E	"	"	—	—	—	—	—	—	—	—	—	—	"	"	"	"	"	"
31	E	56	"	—	—	—	—	—	—	—	—	—	—	5	"	"	"	"	"
32	E	"	"	—	—	—	—	—	—	—	—	—	—	"	"	"	"	"	"
33	E	44	"	—	—	—	—	—	—	—	—	—	—	4¼	"	"	"	"	"
34	E	"	"	—	—	—	—	—	—	—	—	—	—	"	"	"	"	"	"
35																			
36																			
37	B	20	6.5Al-4V	—	—	—	—	—	—	—	—	—	—	5	500	1770-4" TO [illegible]	1750-1HR-WQ	1000-8HR-AC	HEAT TREATED
38	B	"	"	—	—	—	—	—	—	—	—	—	—	"	"	"	"	"	"
39	B	48	"	—	—	—	—	—	—	—	—	—	—	8½	1200	"	"	"	"
40	B	"	"	—	—	—	—	—	—	—	—	—	—	"	"	"	"	"	"
41	B	"	"	—	—	—	—	—	—	—	—	—	—	"	"	"	"	"	"
42	B	"	"	—	—	—	—	—	—	—	—	—	—	"	"	"	"	"	"
43																			
44																			
45	C	47	6Al-4V	—	—	—	—	—	—	—	—	—	—	8½	1000	1750-4" TO [illegible]	1700-2HR-WQ	1000-8HR-AC	HEAT TREATED
46	C	"	"	—	—	—	—	—	—	—	—	—	—	"	"	"	"	"	"
47	C	83	"	—	—	—	—	—	—	—	—	—	—	"	"	"	"	"	"
48	C	"	"	—	—	—	—	—	—	—	—	—	—	"	"	"	"	"	"
49	C	37	"	—	—	—	—	—	—	—	—	—	—	4¼	500	"	"	"	"
50	C	46	"	—	—	—	—	—	—	—	—	—	—	"	190	"	"	"	"
51	C	92	"	—	—	—	—	—	—	—	—	—	—	8½	1000	"	"	"	"
52	C	"	"	—	—	—	—	—	—	—	—	—	—	"	"	"	"	"	"
53	C	40	"	—	—	—	—	—	—	—	—	—	—	5	500	"	"	"	"
54	C	"	"	—	—	—	—	—	—	—	—	—	—	"	"	"	"	"	"
55	C	41	"	—	—	—	—	—	—	—	—	—	—	4¼	500	"	"	"	"
56	C	"	"	—	—	—	—	—	—	—	—	—	—	"	"	"	"	"	"
57																			
58																			
59	B	27	6Al-4V	—	—	—	—	—	—	—	—	—	—	8½	1000	1700-4" TO [illegible]	1650-2HR-WQ	900-24HR-AC	HEAT TREATED
60	B	"	"	—	—	—	—	—	—	—	—	—	—	"	"	"	"	"	"
61	B	95	"	—	—	—	—	—	—	—	—	—	—	"	"	"	"	"	"
62	B	"	"	—	—	—	—	—	—	—	—	—	—	"	"	"	"	"	"
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S

	MECHANICAL PROPERTIES					
	0.2% YIELD STRENGTH - PSI	TENSILE STRENGTH PSI	ELONGATION %	RED. A %	CHARPY IMPACT AT -40°F FT-LBS	TESTED BY
1	152,600	166,600	15.7	42.5	15.1	WD
2	151,300	165,800	15.4	40.4	15.5	"
3	152,600	165,700	16.7	42.1	15.0	"
4	153,100	167,300	15.6	42.4	15.3	"
5						
6						
7	152,000	164,200	15.4	37.1	12.5	WD
8	151,400	163,300	15.4	36.1	12.5	"
9						
10						
11	147,700	158,300	17.1	43.5	14.0	"
12	147,600	159,800	16.6	44.5	13.5	"
13	142,200	—	16.5	48.1	14.0	"
14	148,700	158,700	16.3	45.6	12.5	"
15	142,500	157,000	12.9	36.6	14.0	"
16	143,000	157,300	13.8	33.0	14.5	"
17	145,800	—	13.6	30.1	12.0	"
18	141,700	155,600	15.7	42.0	13.5	"
19	148,700	—	16.6	40.8	13.0	"
20	145,900	—	17.8	39.3	12.3	"
21						
22						
23	140,300	149,600	13.7	34.9	11.0	GOV'T
24	141,300	150,000	13.1	33.1	10.0	"
25	142,000	150,000	14.5	38.8	11.6	"
26	144,000	152,000	14.5	38.5	11.2	"
27	142,000	155,800	16.4	39.4	12.2	"
28	143,000	154,200	10.7	18.6	11.2	"
29	144,000	154,000	18.4	40.2	10.7	"
30	143,500	155,400	15.7	41.5	12.5	"
31	148,000	156,000	16.5	41.6	12.4	"
32	148,500	156,000	16.0	39.8	12.8	"
33	142,500	150,500	17.8	45.5	11.9	"
34	143,500	151,000	17.1	44.1	12.0	"
35						
36						
37	143,300	158,250	17.1	44.9	12.0	GOV'T
38	144,500	157,500	15.0	43.6	12.8	"
39	143,300	159,300	13.5	40.4	11.0	WD
40	144,000	158,200	16.0	43.6	11.8	"
41	145,800	161,200	14.0	35.5	11.8	"
42	145,600	159,100	17.0	46.3	11.0	"
43						
44						
45	142,750	155,750	12.9	41.9	12.1	GOV'T
46	143,500	154,000	15.6	41.5	11.3	"
47	142,000	155,800	16.3	32.6	14.0	"
48	145,500	156,000	13.8	34.9	13.6	"
49	144,000	—	16.3	43.6	11.5	WD
50	145,500	—	16.3	41.6	11.1	"
51	145,500	154,400	17.1	41.1	11.5	GOV'T
52	145,500	154,000	13.6	34.9	13.2	"
53	142,500	155,300	16.6	41.9	11.0	"
54	143,500	152,000	16.6	40.2	12.1	"
55	140,500	153,500	15.0	40.7	12.8	"
56	140,500	153,500	13.8	38.7	13.4	"
57						
58						
59	133,500	148,000	16.9	47.8	12.0	WD
60	138,000	148,500	13.4	46.8	14.0	"
61	132,000	148,000	13.3	38.5	20.0	"
62	135,000	150,500	14.7	39.4	19.0	"
	T	U	V	W	X	Y

19-066-704/ORD-60

TYPICAL METALLURGICAL PROPERTIES
OF ALPHA-BETA TYPE TITANIUM ALLOYS

—— IN ACCORDANCE WITH ——

MILITARY SPECIFICATION MIL-T-46038 (ORD)
(WROUGHT, RODS, BARS AND BILLETS)

TABLE I

WATERTOWN ARSENAL LABORATORIES

DATE: *30 MARCH 1960*

SHEET *2* OF *4*

YIELD STRENGTH RANGE 120,000-159,999 P.S.I. (TANGENTIAL TEST PROPERTIES)

	PRODUCER	HEAT	COMPOSITION %												BILLET		FORGING & HEAT TREAT				MECHANICAL PROPERTIES					
			NOMINAL	AL	V	Sn	Cu	Fe	C	O	H	N	TESTED BY		DIAMETER INCHES	WEIGHT LBS	(°F) UPSET FORGING	(°F) SOLUTION TREATMENT	(°F) AGING TREATMENT	CONDITION	0.1% YIELD STRENGTH-PSI	TENSILE STRENGTH PSI	ELONGATION %	RED. A %	CHARPY IMPACT AT-40°F FT-LBS	TESTED BY
1	B	94	6Al-4V	—	—	—	—	—	—	—	—	—	—		2½	500	1700-4" TO 1½"	1750-2HR-WQ	900-24HR-AC	HEAT TREATED	133,500	148,000	14.7	38.9	12.0	IMD
2	B	"	"	—	—	—	—	—	—	—	—	—	—		"	"	"	"	"	"	132,000	144,800	14.7	36.1	14.0	"
3	B	26	"	—	—	—	—	—	—	—	—	—	—		4½	"	1700-4" TO 1"	"	"	"	132,000	148,000	14.0	47.8	13.0	"
4	B	"	"	—	—	—	—	—	—	—	—	—	—		"	"	"	"	"	"	132,000	148,000	14.7	55.4	14.0	"
5	B	27	"	—	—	—	—	—	—	—	—	—	—		5	"	1700-4" TO 1½"	"	"	"	133,500	148,000	18.9	47.6	12.0	"
6	B	"	"	—	—	—	—	—	—	—	—	—	—		"	"	"	"	"	"	138,000	148,800	18.4	46.6	14.0	"
7	B	00	"	—	—	—	—	—	—	—	—	—	—		8½	1000	1700-4" TO 1"	"	"	"	138,000	149,000	18.4	48.4	28.0	"
8	B	"	"	—	—	—	—	—	—	—	—	—	—		"	"	"	"	"	"	141,000	150,000	14.0	41.6	20.0	"
9	B	69	"	—	—	—	—	—	—	—	—	—	—		"	"	"	"	"	"	139,500	150,000	14.7	39.4	19.5	"
10	B	"	"	—	—	—	—	—	—	—	—	—	—		"	"	"	"		"	144,000	150,000	14.0	41.4	19.5	"
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19-066-705/ORD-60

TYPICAL METALLURGICAL PROPERTIES
OF ALPHA-BETA TYPE TITANIUM ALLOYS

—— IN ACCORDANCE WITH ——

MILITARY SPECIFICATION MIL-T-46038 (ORD)

(WROUGHT, RODS, BARS AND BILLETS)

TABLE I

WATERTOWN ARSENAL LABORATORIES

DATE 30 MARCH 1960

SHEET 3 OF 4

YIELD STRENGTH RANGE 160,000 – 189,999 PSI (TANGENTIAL TEST PROPERTIES)

			COMPOSITION %										BILLET		FORGING & HEAT TREAT				MECHANICAL PROPERTIES					
	PRODUCER	HEAT	NOMINAL	AL	V	Sn	Cu	Fe	C	O	H	N	TESTED BY	DIAMETER INCHES	WEIGHT LBS	(°F) START FORGING	(°F) SOLUTION TREATMENT	(°F) AGING TREATMENT	CONDITION	0.2% YIELD STRENGTH PSI	TENSILE STRENGTH PSI	ELONGATION %	RED. A %	CHARPY IMPACT AT -40°F FT-LBS	TESTED BY
1	A	46-1	Ti-6Al-6V-2Sn	5.75	5.35	1.73	0.24	0.44	0.013	0.15	0.002	0.016	ND	10½	1000	1675-4"TO½"	1660-1HR WQ	1050 4HR AC	HEAT TREATED	171,750	181,000	11.0	38.6	9.6	GOV'T
2	A	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	173,000	180,400	12.0	50.8	8.1	"
3	A	"	"	5.36	5.48	1.92	0.21	0.45	0.028	0.10	0.002	0.022	GOV'T	"	"	"	1675-1¼HR WQ	1000 4HR AC	"	171,000	182,000	8.7	25.0	12.5	ND
4	A	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	166,000	187,000	7.2	25.5	2.5	"
5	A	46-2	"	5.72	5.42	1.72	0.23	0.46	0.015	0.17	0.001	0.013	ND	10½	1000	"	1660 1HR WQ	1050-4HR AC	"	169,500	180,800	11.0	46.2	8.4	GOV'T
6	A	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	171,000	182,400	13.0	39.2	9.7	"
7	A	"	"	5.47	5.47	1.92	0.24	0.49	0.027	0.10	0.002	0.024	GOV'T	"	"	"	1675 1¼HR WQ	1000 4HR AC	"	164,000	179,800	12.1	43.6	11.0	IND
8	A	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	166,000	180,000	10.0	32.6	13.0	"
9	A	46-3	"	5.69	5.39	1.76	0.23	0.46	0.015	0.16	0.002	0.013	IND	9½	1000	"	"	"	"	166,000	182,000	10.0	27.4	10.0	"
10	A	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	165,000	180,000	7.9	17.0	10.0	"
11	A	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	172,800	190,300	8.0	30.0	15.0	"
12	A	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	167,000	186,400	9.3	27.0	15.0	"
13	A	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	170,000	189,200	8.0	18.1	13.0	"
14	A	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	165,000	186,000	10.7	32.1	15.0	"
15	A	95-1	"	5.33	5.50	1.92	0.20	0.46	0.016	0.08	0.002	0.036	"	7½	600	1675 4"TO1"	"	1050 4HR AC	"	169,300	183,300	10.0	29.0	10.0	"
16	A	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	169,600	183,300	9.5	27.4	10.0	"
17	A	"	"	5.62	5.51	1.91	0.20	0.42	0.017	0.14	0.004	0.041	"	"	"	"	"	"	"	171,600	184,000	10.0	27.4	10.0	"
18	A	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	173,200	184,800	7.9	19.6	10.0	"
19	A	"	"	5.45	5.56	2.34	0.26	0.51	0.018	0.13	0.004	0.037	GOV'T	"	"	"	1630 ½HR WQ	"	"	178,000	185,000	9.3	23.1	7.3	GOV'T
20	A	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	177,000	189,000	10.7	28.9	7.8	"
21	A	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	178,500	184,000	12.1	26.0	7.3	"
22	A	95-2	"	5.50	5.48	1.81	0.20	0.48	0.017	0.12	0.007	0.033	IND	8½	800	"	NONE	1100 2HR AC	"	166,400	180,700	11.4	44.0	9.0	IND
23	A	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	168,300	181,900	11.4	41.9	9.5	"
24	A	"	"	5.60	5.38	1.82	0.20	0.42	0.018	0.14	0.002	0.030	"	"	"	"	"	"	"	169,800	182,600	11.4	43.7	10.9	"
25	A	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	170,000	182,800	10.0	31.2	9.0	"
26	A	"	"	5.40	5.53	2.32	0.27	0.52	0.016	0.13	0.004	0.034	GOV'T	"	"	—	—	—	—	—	—	—	—	—	—
27	A	02	"	5.64	5.20	1.92	0.28	0.41	0.012	0.15	0.002	0.040	IND			1675 4"TO1"	1675 1½HR WQ	1050-4HR-AC	HEAT TREATED	168,500	181,300	9.3	26.5	9.0	IND
28	A	"	"	"	"	"	"	"	"	"	"	"	"			"	"	"	"	170,800	182,500	8.6	21.6	—	"
29	A	"	"	5.47	5.26	2.26	0.29	0.47	0.014	0.15	0.004	0.041	GOV'T			—	—	—	—	—	—	—	—	—	—
30	A	95-1	"	5.62	5.51	1.91	0.20	0.42	0.017	0.13	0.004	0.041	IND	7½	800	1750 4"TO1"	NONE	1300-2HR-AC	ANNEALED	152,990	167,050	15.6	48.2	12.0	IND
31	A	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	1100 2HR-AC	AS FORGED	143,690	158,710	17.0	49.5	15.0	"
32	A	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	149,500	163,130	15.0	44.3	16.0	"
33																									
34																									
35	B	17	Ti-6Al-6V-2Sn	5.60	5.30	2.00	0.30	0.54	0.026	0.14	0.004	0.019	IND	10½	3200	1675-5½TO 1½"	1630 ½HR-WQ	1050 4HR-AC	HEAT TREATED	170,400	185,500	10.0	23.1	8.5	IND
36	B	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	173,200	187,700	10.0	29.8	8.5	"
37	B	25	"	5.60	5.60	1.90	0.32	0.56	0.024	0.15	0.004	0.016	"	10½	1200	1675-4"TO¾"	NONE	1100-4HR-AC	"	174,500	185,700	7.0	23.7	7.5	"
38	B	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	176,500	188,700	9.0	21.8	9.0	"
39	B	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	177,300	190,300	8.5	16.7	5.0	"
40	B	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	177,200	191,000	12.0	24.7	8.0	"
41	B	"	"	"	"	"	"	"	"	"	"	"	"	14	1200	1630-4"TO¾"	1630-1HR-WQ	1050-4HR-AC	"	177,400	—	11.0	36.3	5.5	"
42	B	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	179,000	—	10.0	33.0	9.0	"
43	B	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	177,700	—	10.0	30.5	8.5	"
44	B	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	177,300	—	10.0	28.5	7.5	"
45	B	26	"	5.60	5.40	2.00	0.26	0.56	0.025	0.14	0.004	0.020	"	6½	800	"	"	"	"	178,500	—	10.0	35.7	6.5	"
46	B	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	181,300	—	9.0	21.7	6.5	"
47	B	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	176,700	—	13.0	40.4	9.0	"
48	B	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	181,800	—	9.0	33.0	7.0	"
49	B	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	176,500	—	11.0	29.2	6.5	"
50	B	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	178,900	—	10.0	33.1	5.0	"
51	B	99	"	5.60	5.50	2.00	—	0.50	0.025	0.13	0.004	0.020	"	11	1000	1625-4"TO¾"	NONE	1100 4HR AC	"	165,800	172,800	15.0	37.1	10.5 — 11.0	"
52	B	"	"	5.50	5.80	1.98	0.41	0.75	0.013	0.14	0.002	0.019	GOV'T	"	"	1675-4"TO¾"	1630-1HR-WQ	"	"	170,000	177,500	10.7	33.5	6.6	GOV'T
53	B	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	169,000	176,000	11.4	36.7	6.6	"
54	B	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	NONE	"	"	175,700	183,000	10.0	33.7	10.0	IND
55	B	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	173,100	183,800	13.0	30.7	11.0	"
56	B	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	1630-1½HR-WQ	"	"	170,000	177,000	11.0	35.0	8.5	GOV'T
57	B	00	"							0.13	0.002		"	11	1000	"	"	"	"	170,000	178,000	12.1	35.8	8.1	"
58	B	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	172,000	180,000	11.4	38.0	9.5	"
59	B	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	171,000	179,000	11.7	36.9	8.8	"
60	B	20	"	5.50	5.40	2.18	0.30	0.84	0.033	0.12	0.003	0.026	"	9½	1000	"	1650-1HR-WQ	1150-4HR-AC	"	169,700	184,200	8.0	25.7	7.5	IND
61	B	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	173,300	184,200	7.0	21.8	8.0	"
62	B	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	170,800	183,200	8.0	20.2	8.0	"
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y

19-066-706/ORD-60

TYPICAL METALLURGICAL PROPERTIES
OF ALPHA-BETA TYPE TITANIUM ALLOYS

—— IN ACCORDANCE WITH ——

MILITARY SPECIFICATION MIL-T-46038 (ORD)
(WROUGHT, RODS, BARS AND BILLETS)

TABLE I

WATERTOWN ARSENAL LABORATORIES
DATE: 30 MARCH 1960
SHEET 4 OF 4

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

	PRODUCER	HEAT	COMPOSITION % NOMINAL	AL	V	Sn	Cu	Fe	C	O	H	N	TESTED BY	BILLET DIAMETER INCHES	BILLET WEIGHT LBS	FORGING & HEAT TREAT (°F) UPSET FORGING	(°F) SOLUTION TREATMENT	(°F) AGING TREATMENT	CONDITION	MECHANICAL PROPERTIES 0.1% YIELD STRENGTH - PSI	TENSILE STRENGTH PSI	ELONGATION %	RED A %	CHARPY IMPACT AT -40°F FT-LBS	TESTED BY
1	B	20	~~Ti-6Al-6V-2Sn~~	5.30	5.40	2.16	0.30	0.84	0.013	0.12	0.0030	0.026	GOV'T	9 ¼	1000	1675-4" TO ¾"	1650-1HR-WQ	1150-4HR-AC	HEAT TREATED	164,200	178,400	10.0	23.6	8.0	IND
2	B	62	"	5.12	5.54	2.01	0.25	0.52	—	—	—	0.063	IND	7 ¼	300	1675-4" TO 1"	—	—	AS FORGED	138,100	158,300	12.0	36.7	—	"
5	C	37	~~Ti-6Al-6V-2Sn~~	5.80	5.80	2.90	0.62	0.84	0.03	0.18	0.006	0.030	IND	8 ¼	1000	1675-4" TO ¾"	1630-1½HR-WQ	1100-4HR-AC	HEAT TREATED	170,000	179,800	15.0	39.1	7.5	IND
6	C	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	173,500	184,800	12.9	27.6	9.6	"
7	C	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	1150-4HR-AC	"	170,900	184,000	7.9	24.1	10.5	"
8	C	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	176,500	191,000	11.4	23.1	8.0	"
9	C	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	1250-4HR-AC	ANNEALED	152,000	164,200	18.4	37.1	12.6	"
10	C	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	151,400	163,500	16.4	36.1	10.5	"
13	D	97	~~Ti-6Al-6V-2Sn~~	5.22	5.09	2.28	0.33	0.64	0.04	0.14	0.0060	0.037	IND	4	200	1650-4" TO ¾"	1650-1HR-WQ	1100-4HR-AC	HEAT TREATED	169,000	180,000	10.0	27.3	9.0	IND
14	D	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	167,000	178,000	9.0	21.8	9.5	"
15	D	"	"	"	"	"	"	"	"	"	"	"	"	"	"	1700-4" TO 1"	1625-1HR-WQ	"	"	18[illegible],000	203,000	8.5	16.7	—	"
16	D	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	189,000	197,000	8.0	23.2	—	"
17	D	"	"	"	"	"	"	"	"	"	"	"	"	"	"	1675-4" TO ¾"	1600-1½HR-WQ	1050-4HR-WQ	"	186,000	195,200	9.0	26.8	7.2	GOV'T
18	D	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	189,000	199,000	7.0	16.2	6.3	"
19	D	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	1100-4HR-AC	"	187,000	197,000	7.0	17.0	7.7	"
20	D	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	177,000	187,800	9.0	23.4	6.8	"
23	TMCA	80	Ti-155A	—	—	—	—	—	—	—	—	—	IND	8 ¼	4000	1675-4" TO ¾"	1675-1HR-WQ	1100-2HR-AC	HEAT TREATED	169,800	183,300	11.5	31.2	8.0	IND
24	TMCA	"	"	—	—	—	—	—	—	—	—	—	"	"	"	"	"	"	"	171,300	184,800	12.0	31.7	8.0	"
25	TMCA	"	"	—	—	—	—	—	—	—	—	—	"	"	"	"	"	"	"	170,200	182,700	10.0	29.8	9.5	"
26	TMCA	"	"	—	—	—	—	—	—	—	—	—	"	"	"	"	"	"	"	170,600	181,700	9.5	19.5	8.5	"
27	TMCA	78	"	—	—	—	—	—	—	—	—	—	"	8	500	"	1650-1HR-WQ	1100-4HR-AC	"	171,800	182,100	12.0	32.6	8.0	"
28	TMCA	"	"	—	—	—	—	—	—	—	—	—	"	"	"	"	"	"	"	171,600	181,300	11.0	31.5	8.0	"
29	TMCA	28	"	—	—	—	—	—	—	—	—	—	"	8	500	"	"	"	"	172,600	184,300	9.5	28.8	8.0	"
30	TMCA	"	"	—	—	—	—	—	—	—	—	—	"	"	"	"	"	"	"	166,100	176,600	11.5	42.0	9.0	"
31	TMCA	27	"	—	—	—	—	—	—	—	—	—	"	4 5/16	2800	1675-4" TO ¾"	1675-1HR-WQ	1000-6HR-AC	"	177,100	—	12.0	28.1	7.0	"
32	TMCA	"	"	—	—	—	—	—	—	—	—	—	"	"	"	"	"	"	"	185,100	—	9.0	32.8	8.0	"
33	TMCA	"	"	—	—	—	—	—	—	—	—	—	"	"	"	"	"	"	"	174,000	—	12.0	21.7	7.9	"
34	TMCA	"	"	—	—	—	—	—	—	—	—	—	"	"	"	"	"	"	"	181,500	—	9.0	23.1	6.5	"
37	C	20	~~Ti-6Al-6V-2Sn~~	5.40	5.60	2.16	0.22	0.47	0.04	0.22	—	0.061	IND	10 ¾	6000	1675-4" → ¾"	1670-1½HR-WQ	1100-4HR-AC	HEAT TREATED	[illegible]	200,500	7.[illegible]	17.2	4.5	IND
38	C	"	"	"	"	"	"	"	"	"	—	"	"	"	"	"	"	"	"	186,800	197,700	8.2	27.2	4.5	"
39	C	"	"	"	"	"	"	"	"	"	—	"	"	"	"	"	"	"	"	185,000	194,700	[illegible]	18.7	4.5	"
40	C	"	"	"	"	"	"	"	"	"	—	"	"	"	"	"	"	"	"	185,000	194,000	9.3	17.1	5.0	"
41	C	24	"	5.70	5.60	2.32	0.22	0.46	0.04	0.24	—	0.060	"	"	"	"	"	"	"	189,100	189,300	7.9	15.3	5.5	"
42	C	"	"	"	"	"	"	"	"	"	—	"	"	"	"	"	"	"	"	190,000	199,100	8.6	17.7	6.0	"

A B C D E F G H I J K L M N O P Q R S T U V W X Y

19-066-701/ORD-60

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 Y.S. (.1%) RANGE REQUIREMENT (PSI)	ACTUAL (.1% Y.S.) (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		BACKWARD EXTRUSION	1700-½HR-WQ	1100-2HR-AC	143,000-162,999	161,000	173,600	14.0	41.0	10.8
2	"	"	"	"	"	"	"	"	"	"	"	"	165,000	172,800	12.0	41.0	10.8
3	"	"	"	"	"	"	"	"	"	"	"	"	160,500	170,800	17.0	42.4	10.2
4	"	"	"	"	"	"	"	"	"	"	"	"	161,000	173,600	15.0	43.4	10.7
5	"	"	"	"	"	"	"	"	"	"	"	"	163,000	172,200	15.0	43.4	10.2
6	"	"	"	"	"	"	"	"	"	"	"	"	160,000	170,600	14.0	41.6	9.8
7	"	D-66	"	545	1	1	"	1	CLOSED DIE FORGING	"	1100-4HR-AC	130,000-169,999	161,500	166,400	13.0	53.4	12.0
8	"	"	"	"	"	"	"	"	"	"	"	"	160,000	164,400	14.0	37.8	12.3
9																	
10																	
11	WTN ARSENAL	TMCA-27	Ti-155A	680	4⅝	8	1675-WQ	1	CLOSED DIE FORGING	1610-1HR-WQ	1250-4HR-AC	140,000-159,999	148,000	162,400	17.1	28.4	12.7
12	"	"	"	"	"	"	"	"	"	"	"	"	152,000	165,800	19.3	38.8	9.9
13	"	"	"	"	"	"	"	"	"	"	"	"	153,000	166,800	15.7	29.4	11.7
14	"	"	"	"	"	"	"	"	"	"	"	"	155,500	167,200	15.7	34.5	11.1
15	"	"	"	"	"	"	"	"	"	"	"	"	155,500	163,250	17.9	46.1	10.1
16	"	"	"	"	"	"	"	"	"	"	"	"	157,500	164,250	17.1	33.1	9.8
17	"	CC42	6.5-Al-4V	"	"	"	"	"	"	1700-1½HR-WQ	1100-6HR-AC	"	157,000	165,800	12.0	39.2	8.9
18	"	"	"	"	"	"	"	"	"	"	"	"	156,000	165,200	10.0	36.6	9.9
19	"	E-47	"	"	"	"	"	"	"	"	1050-4HR-AC	"	160,500	174,800	13.0	34.8	10.8
20	"	"	"	"	"	"	"	"	"	"	"	"	158,750	171,800	10.0	26.0	13.1
21	"	D-73	"	307	2	1½	1750-WQ	1	"	"	1100-4HR-AC	"	158,500	167,000	15.0	47.4	13.5
22	"	"	"	"	"	"	"	"	"	"	"	"	146,500	165,600	13.0	41.4	11.1
23	"	D-72	"	018	1	1½	"	"	"	"	"	"	155,500	162,300	15.0	38.9	12.3
24	"	"	"	"	"	"	"	"	"	"	"	"	155,500	164,500	15.7	38.9	12.0
25	"	"	"	"	"	"	"	"	"	"	"	"	151,300	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	166,400	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-WQ	1100-2HR-AC	135,000-154,999	142,250	149,500	17.1	47.8	9.7
33	"	"	"	"	"	"	"	"	"	"	"	"	148,000	151,000	16.4	44.1	9.2
34	"	E-55	"	"	"	"	"	"	"	"	"	"	140,000	148,500	17.1	44.5	9.5
35	"	"	"	"	"	"	"	"	"	"	"	"	140,000	147,500	17.1	44.5	9.5
36	"	E-40	"	153	3	11	2000-WQ	1	"	—	1500-2HR-AC	125,000-144,999	141,500	157,200	11.4	22.1	11.7
37	"	"	"	"	"	"	"	"	"	—	"	"	140,500	155,200	11.4	24.8	11.1
38	"	E-54	"	163	8½	85	1750-WQ	"	BACKWARD EXTRUSION	1675-½HR-WQ	1200-3HR-AC	135,000-154,999	145,000	154,000	15.7	44.1	10.0
39	"	"	"	"	"	"	"	"	"	"	"	"	148,000	154,750	14.3	34.0	10.9
40	"	"	"	"	"	"	"	"	"	"	"	"	147,000	155,500	12.1	37.1	10.5
41	"	"	"	"	"	"	"	"	"	"	"	"	146,500	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	156,600	15.0	41.0	11.1
43	"	"	"	"	"	"	"	"	"	—	"	"	143,000	158,800	15.5	44.0	10.3
44	"	E-57	"	"	"	"	"	"	"	—	"	"	146,000	157,200	15.0	41.0	9.9
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	"	"	"	"	"	"	"	"	"	—	"	"	146,500	155,200	15.5	38.6	10.0
50																	
51																	
52	WTN ARSENAL	E-38	6.5-Al-4V	127	2	2½	1750-WQ	1½	CLOSED DIE FORGING	—	1250-2HR-AC	125,000-144,999	136,600	151,200	15.0	41.5	10.1
53	"	"	"	"	"	"	"	"	"	—	"	"	138,000	150,800	16.5	44.0	10.1
54	"	E-40	"	153	3	11	2000-WQ	"	"	—	1500-2HR-AC	"	137,500	153,250	13.6	22.1	10.3
55	"	"	"	"	"	"	"	"	"	—	"	"	138,500	153,250	14.3	23.1	10.9
56	"	E-54	"	163	8½	85	1750-WQ	"	BACKWARD EXTRUSION	1675-½HR-WQ	1200-3HR-AC	135,000-154,999	138,000	149,600	11.4	24.1	11.2
57	"	"	"	"	"	"	"	"	"	"	"	"	139,500	148,400	12.1	34.5	10.9
58	"	E-55	"	164	"	"	"	"	"	"	"	"	136,000	147,600	10.7	24.8	12.5
59	"	"	"	"	"	"	"	"	"	"	"	"	135,000	145,000	12.1	28.4	13.0
60	"	"	"	"	"	"	"	"	"	"	"	"	135,100	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

19-066-708/ORD-60

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	6½	85	1750 - AC	1½	BACKWARD EXTRUSION	1750-2HR-WQ	1200-4HR-AC	125,000 - 144,999	127,300	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	12.8
4	"	"	"	"	"	"	"	"	"	"	"	"	125,000	135,500	13.6	36.3	11.7
5	"	E-47	"	106	"	"	"	"	"	"	"	"	127,600	143,000	17.9	34.9	11.8
6	"	"	"	"	"	"	"	"	"	"	"	"	128,750	143,000	19.3	38.9	12.7
7	"	"	"	"	"	"	"	"	"	"	"	"	128,000	143,800	18.0	32.2	11.2
8	"	"	"	"	"	"	"	"	"	"	"	"	130,300	147,000	14.3	32.6	12.1
9	"	E-39	"	142	5	30	"	2	CLOSED DIE FORGING	—	1050-3HR-AC	"	129,000	139,000	18.4	41.5	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
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19-066-703/ORD-60

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 (PSI)	ACTUAL .1% Y.S. (PSI)	TENSILE STRENGTH (PSI)	ELONGATION (%)	RED. A (%)	V NOTCH CHARPY IMPACT AT -40°F (FT LBS)
1	G	B-17	6Al-6V-6Sn	605	10 1/4	220	1675 (MAX) - AC	1/2	FORWARD EXTRUSION	1630-1/2 HR-WQ	1050-4HR-AC	170,000 - 189,999	188,400	196,500	6.7	9.0	6.5
2	G	"	"	"	"	"	"	"	"	"	"	"	185,300	195,300	9.3	11.5	6.5
3	G	"	"	"	"	"	"	"	"	"	"	"	185,900	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	13.4	7.0
7	G	"	"	"	"	"	"	"	"	"	"	"	187,600	197,500	8.0	19.9	7.0
8	G	"	"	"	"	"	"	"	"	"	"	"	189,100	201,500	6.7	11.9	7.5
9	G	"	"	"	"	"	"	"	"	"	"	"	187,600	199,800	6.7	15.4	6.0
10	G	"	"	"	"	"	"	"	"	"	"	"	187,100	198,300	6.7	14.4	7.0
11	G	"	"	"	"	"	"	"	"	"	1100-4HR-AC	"	176,000	—	10.9	21.4	6.7
12	G	"	"	"	"	"	"	"	"	"	"	"	180,500	—	7.8	17.8	7.3
13	G	"	"	"	"	"	"	"	"	"	"	"	186,000	—	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	7.5
17	G	A-46-2	"	"	"	"	"	"	"	"	"	"	172,500	188,000	7.8	15.4	9.2
18	G	"	"	"	"	"	"	"	"	"	"	"	172,200	183,500	6.3	14.4	7.6
19	G	"	"	"	"	"	"	"	"	"	"	"	174,000	188,000	9.4	23.4	8.8
20	G	"	"	"	"	"	"	"	"	"	"	"	176,000	190,000	4.7	11.9	8.1
21	G	"	"	"	"	"	"	"	"	"	"	"	174,000	186,500	9.4	19.9	8.5
22	G	"	"	"	"	"	"	"	"	"	"	"	170,000	186,000	6.3	11.9	8.9
23	G	A-46-01	"	"	"	"	"	"	"	"	"	"	180,000	188,000	7.8	22.5	9.2
24	G	"	"	"	"	"	"	"	"	"	"	"	175,000	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	7/16	"	1630-1HR-WQ	1150-4HR-AC	"	162,500	182,500	8.8	24.0	8.4
28	I	B-00	"	"	"	"	"	"	"	"	1050-4HR-AC	"	170,500	187,500	10.0	18.5	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	"	"	"	"	"	"	"	"	"	"	"	172,500	189,000	10.0	20.0	8.6
32	I	"	"	"	"	"	1775	"	"	1680-1 1/2 HR-WQ	1150-4HR-AC	"	170,200	187,000	2.5	15.4	7.0
33	I	"	"	"	"	"	"	"	"	1630-1 1/2 HR-WQ	1050-4HR-AC	"	160,000	181,200	6.3	20.8	8.5
34	I	B-00	"	"	"	"	1800	"	"	"	"	"	181,700	198,500	7.5	14.5	8.3
35	I	B-99	"	"	"	"	1850	"	"	"	"	"	187,500	208,700	5.0	11.2	6.8
36	I	"	"	"	"	"	"	"	"	"	"	"	188,200	199,000	7.5	15.3	6.5
37	I	"	"	"	"	"	"	"	"	1630-1HR-WQ	"	"	167,500	185,000	7.5	20.1	9.0
38	I	"	"	"	"	"	"	"	"	"	"	"	169,000	185,000	7.5	20.1	8.8
39	I	"	"	"	"	"	"	"	"	"	"	"	180,000	202,000	2.5	3.2	8.4
40	I	"	"	"	"	"	"	"	"	"	"	"	178,000	199,000	7.5	15.0	5.8
41	I	B-00	"	"	"	"	"	"	"	"	"	"	177,000	196,000	5.0	11.8	6.0
42	I	"	"	"	"	"	"	"	"	1680-1 1/2 HR-WQ	1150-4HR-AC	"	171,400	185,700	10.0	32.0	8.0
43	I	"	"	"	"	"	"	"	"	"	"	"	170,600	186,900	7.5	15.3	6.5
44	I	"	"	"	"	"	"	"	"	1630-1HR-WQ	"	"	163,600	184,500	5.0	11.2	9.1
45	G	TMCA-28	Ti-155A	"	10 1/4	250	1700	1/4	"	1675 1 1/2 HR WQ	1100-4HR-AC	"	179,000	>190,000	7.0	23.0	6.5
46	G	"	"	"	"	"	"	"	"	"	"	"	182,000	"	8.5	18.8	7.5
47	G	"	"	"	"	"	"	"	"	"	"	"	181,000	"	9.0	24.3	7.7
48	G	"	"	"	"	"	"	"	"	"	"	"	187,000	"	9.4	25.2	7.8
49	G	"	"	"	"	"	"	"	"	"	"	"	189,000	"	8.8	24.6	7.8
50	G	"	"	"	"	"	"	"	"	"	"	"	180,000	"	8.5	20.5	7.5
51	G	"	"	"	"	"	"	"	"	"	"	"	176,000	"	7.0	22.5	6.4
52	G	"	"	"	"	"	"	"	"	"	"	"	189,000	"	7.8	18.3	7.5
53	G	"	"	"	"	"	"	"	"	"	"	"	186,000	"	7.5	17.7	8.1
54	G	"	"	"	"	"	"	"	"	"	"	"	180,000	"	8.0	21.5	5.4
55	G	"	"	"	"	"	"	"	"	"	"	"	189,000	"	8.6	23.0	6.6
56	G	"	"	"	"	"	1725	"	"	"	"	"	181,000	"	9.5	28.1	7.2
57	G	"	"	"	"	"	"	"	"	"	"	"	183,000	"	8.0	21.9	7.8
58	G	"	"	"	"	"	1750	"	"	"	"	"	173,000	"	7.5	20.0	6.5
59	G	"	"	"	"	"	"	"	"	"	"	"	183,000	"	8.0	18.4	7.4
60	G	"	"	"	"	"	"	"	"	"	"	"	187,000	"	7.1	21.3	7.3
61	G	"	"	"	"	"	"	"	"	"	"	"	185,000	"	8.6	19.1	7.8
62	G	"	"	"	"	"	"	"	"	"	"	"	177,000	"	7.5	20.	7.2
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q

19-066-707/ORD-60

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

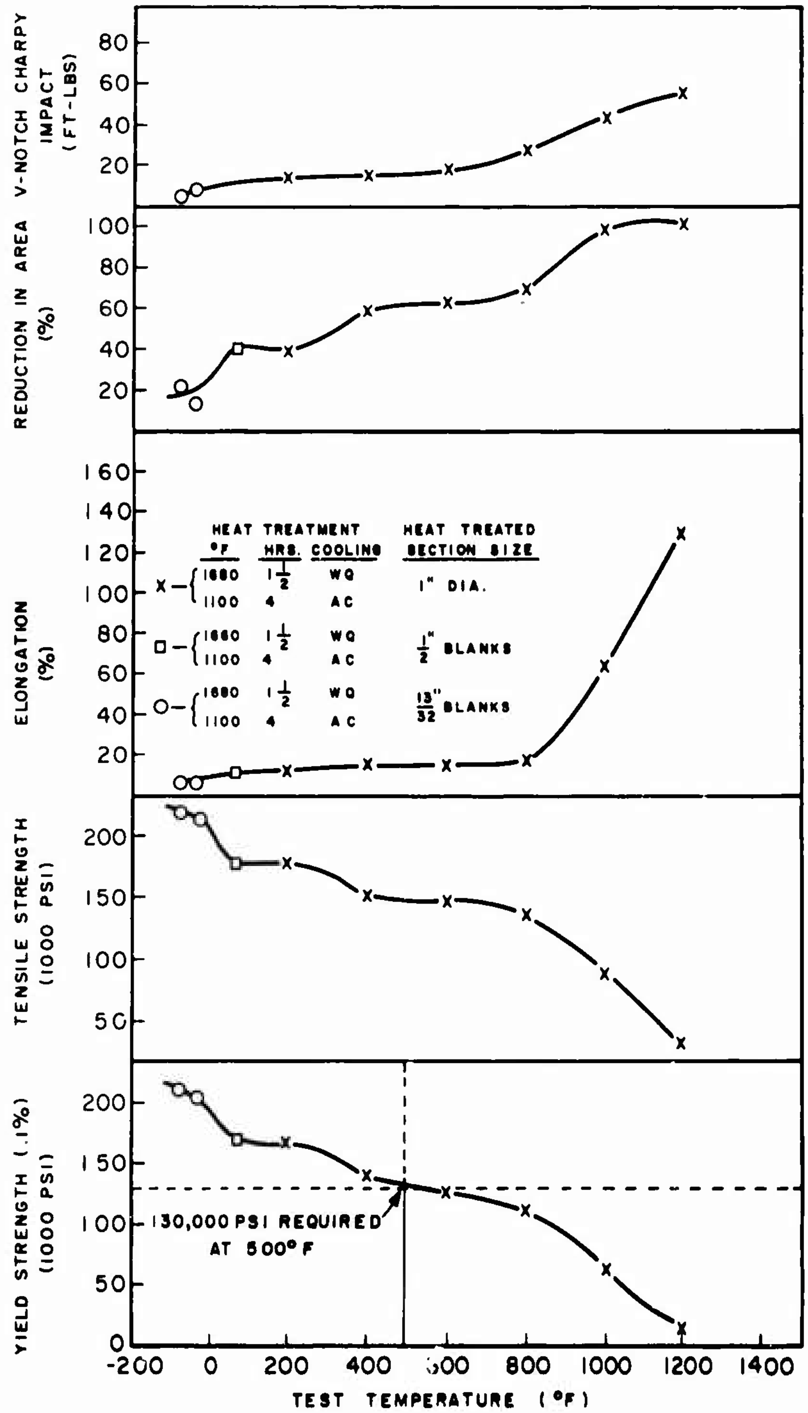
DATE 1 APRIL 1960

SHEET 4 OF 4

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

					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 Y.S. (.2%) RANGE REQUIREMENT (PSI)	ACTUAL .2% Y.S. (PSI)	TENSILE STRENGTH (PSI)	ELONGATION (%)	RED. A (%)	V-NOTCH CHARPY IMPACT AT -40°F (FT-LBS)
1	WTN ARSENAL	TMCA-11	Ti-155A	604	3½	9	1700-WQ	1	CLOSED DIE FORGING	1650-½HR-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	″	″	″	″	″	″	″	″	″	″	″	167,800	174,600	9.0	22.8	8.1
4	WTN ARSENAL	″	″	″	″	″	″	″	″	″	″	″	167,800	185,200	10.0	21.2	7.3
5	WTN ARSENAL	TMCA-80	″	″	″	″	″	″	″	1660-½HR-WQ	″	″	180,200	188,000	9.0	28.8	8.2
6	WTN ARSENAL	TMCA-53	″	″	″	″	″	″	″	″	″	″	178,000	193,000	8.0	15.4	8.1
7	WTN ARSENAL	″	″	″	″	″	″	″	″	″	″	″	176,000	192,000	7.0	17.7	8.1
8	WTN ARSENAL	″	″	″	″	″	″	″	″	″	″	″	180,000	193,600	8.0	17.0	7.3
9	WTN ARSENAL	″	″	″	″	″	″	″	″	″	″	″	181,000	194,800	8.0	15.8	7.1
10	WTN ARSENAL	″	″	″	″	″	″	″	″	″	″	″	177,000	188,400	8.0	21.2	8.1
11	WTN ARSENAL	″	″	″	″	″	″	″	″	″	″	″	178,000	188,800	8.0	21.8	7.7
12	WTN ARSENAL	TMCA-11	″	608	″	10	″	1	OPEN DIE FORGING	″	1050-4HR-AC	″	170,000	181,200	7.0	15.8	8.7
13	WTN ARSENAL	″	″	″	″	″	″	″	″	″	″	″	171,500	180,400	7.0	15.8	7.0
14	WTN ARSENAL	″	″	″	″	″	″	″	″	1610-1HR-WQ	″	″	170,000	181,500	12.5	23.4	6.0
15	WTN ARSENAL	″	″	″	″	″	″	″	″	″	″	″	167,500	183,000	9.4	16.8	5.8
16	H	B-20	6Al-6V-2Sn	63-B	9½	250	1750-AC	″	FORWARD EXTRUSION	1660-½HR-WQ	1125-4HR-AC	″	174,000	184,000	6.0	12.8	7.8
17	H	″	″	″	″	″	″	″	″	″	″	″	173,000	183,000	6.1	13.2	6.1
18	H	″	″	″	″	″	″	″	″	1630-½HR-WQ	″	″	170,000	186,000	6.1	13.8	7.8
19	H	″	″	″	″	″	″	″	″	″	″	″	170,500	186,400	6.2	13.0	7.8
20	G	B-99	″	63-C	10½	70	1650 (MAX)-AC	1	FORWARD EXTRUSION (EXPANDED)	″	1050-4HR-AC	″	168,000	183,800	8.0	16.4	8.8
21	G	″	″	″	″	″	″	″	″	″	″	″	178,500	188,800	9.0	25.4	8.4
22	G	″	″	″	″	″	″	″	″	″	″	″	178,000	188,200	7.0	17.0	8.7
23	G	″	″	″	″	″	″	″	″	″	″	″	178,000	187,600	7.5	21.8	8.4
24	G	″	″	″	″	″	″	″	″	″	″	″	179,000	192,000	8.0	14.7	7.8
25	G	″	″	″	″	″	″	″	″	″	″	″	178,000	188,000	8.0	18.4	8.8
26	G	″	″	″	″	″	″	″	″	″	″	″	177,500	188,400	9.0	28.4	8.8
27	G	″	″	″	″	″	″	″	″	″	″	″	174,000	188,200	9.0	22.8	8.4
28	G	″	″	″	″	″	″	″	″	″	″	″	173,000	182,800	8.0	21.8	8.4
29	G	″	″	″	″	″	″	″	″	″	″	″	171,500	181,600	11.0	23.4	6.8
30	G	″	″	″	″	″	″	″	″	″	″	″	174,300	190,200	8.5	18.5	10.0
31	G	″	″	″	″	″	″	″	″	″	″	″	171,400	189,700	9.0	14.8	—
32	G	″	″	″	″	″	″	″	″	″	″	″	186,500	202,800	8.0	13.8	8.8
33	G	″	″	″	″	″	″	″	″	″	″	″	178,500	191,800	7.0	14.8	8.8
34	G	″	″	″	″	″	″	″	″	″	″	″	181,800	197,900	7.0	12.4	8.0
35	G	″	″	″	″	″	″	″	″	″	″	″	179,500	198,800	7.5	15.5	8.0
36	WTN ARSENAL	B-20	″	63-N	9½	50	1675-WQ	1½	OPEN DIE FORGING	″	1100-6HR-AC	″	178,250	—	8.0	13.1	7.8
37	WTN ARSENAL	″	″	″	″	″	″	″	″	″	″	″	174,500	—	8.5	24.4	7.0
38	WTN ARSENAL	B-99	″	″	″	″	″	″	″	″	″	″	184,800	—	7.0	21.8	6.0
39	WTN ARSENAL	″	″	″	″	″	″	″	″	″	″	″	178,500	191,400	6.1	14.5	7.0
40	WTN ARSENAL	″	″	″	″	″	″	″	″	″	″	″	182,300	—	6.6	17.8	8.1
41	WTN ARSENAL	B-25	″	DE-2	3½	8	″	1	CLOSED DIE FORGING	″	″	″	174,000	184,800	10.0	18.2	7.5
42	WTN ARSENAL	″	″	″	″	″	″	″	″	″	″	″	174,500	186,000	10.0	27.4	7.0
43																	
44																	
45	WTN ARSENAL	TMCA-80	Ti-155A	121	9½	40	1725-WQ	1	BACKWARD EXTRUSION	1625-½HR-WQ	1100-6HR-AC	160,000-179,999	168,300	178,200	12.0	30.8	7.0
46	WTN ARSENAL	″	″	″	″	″	″	″	″	″	″	″	168,000	184,800	10.0	23.8	6.0
47	WTN ARSENAL	″	″	″	″	″	″	″	″	″	″	″	166,000	179,000	12.5	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	″	″	″	″	″	″	1660-½HR-WQ	1200-6HR-AC	″	160,000	174,000	10.0	21.2	7.8
50	WTN ARSENAL	″	″	″	″	″	″	″	″	″	″	″	165,000	178,000	8.0	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	38.8	8.1
53	WTN ARSENAL	TMCA-80	Ti-155A	118	″	″	″	″	″	1675-½HR-WQ	1100-6HR-AC	″	167,300	184,000	6.4	14.0	8.8
54	WTN ARSENAL	″	″	″	″	″	″	″	″	″	″	″	170,000	180,500	8.8	25.1	7.0
55	WTN ARSENAL	″	″	″	″	″	″	″	″	″	″	″	171,650	180,500	8.7	15.0	8.7
56	WTN ARSENAL	″	″	″	″	″	″	″	″	″	″	″	172,300	183,750	7.8	18.1	8.3
57	WTN ARSENAL	″	″	″	″	″	″	″	″	″	″	″	167,000	188,250	4.5	8.7	8.2
58	WTN ARSENAL	″	″	″	″	″	″	″	″	″	″	″	168,000	184,500	7.1	11.4	8.8
59	WTN ARSENAL	A-95-1	6Al-6V-2Sn	″	″	″	″	″	″	1660-½HR-WQ	1200-6HR-AC	″	166,000	177,500	7.8	25.8	8.1
60	WTN ARSENAL	″	″	″	″	″	″	″	″	″	″	″	166,500	177,800	10.0	25.1	8.8
61	WTN ARSENAL	″	″	″	″	″	″	″	″	″	″	″	165,000	175,000	11.4	28.4	9.9
62	WTN ARSENAL	″	″	″	″	″	″	″	″	″	″	″	165,000	175,000	10.7	34.8	9.7
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q

19-066-702/ORD-60

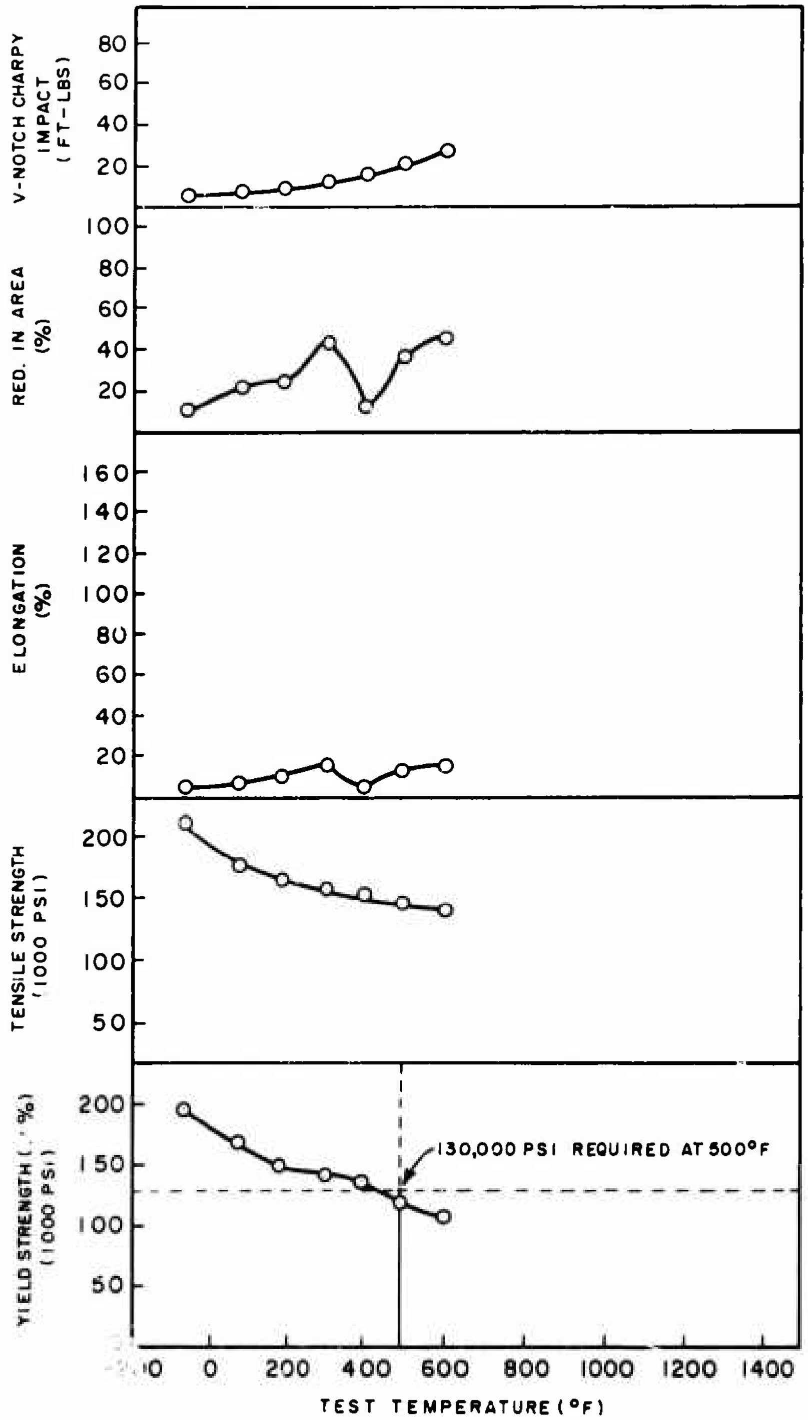


MECHANICAL PROPERTIES OF Ti-6Al-6V-2Sn ALLOY – LONGITUDINAL TEST SPECIMENS – BARSTOCK FORGED FROM 2 5/8" DIAMETER AT 1900°F TO 1" SQUARE – REHEATED TO 1700°F – FORGED 1" DIAMETER AND AIR COOLED.

WAL - SPS
MAY 20, 1959

19-066-732/ORD-60

FIGURE 1

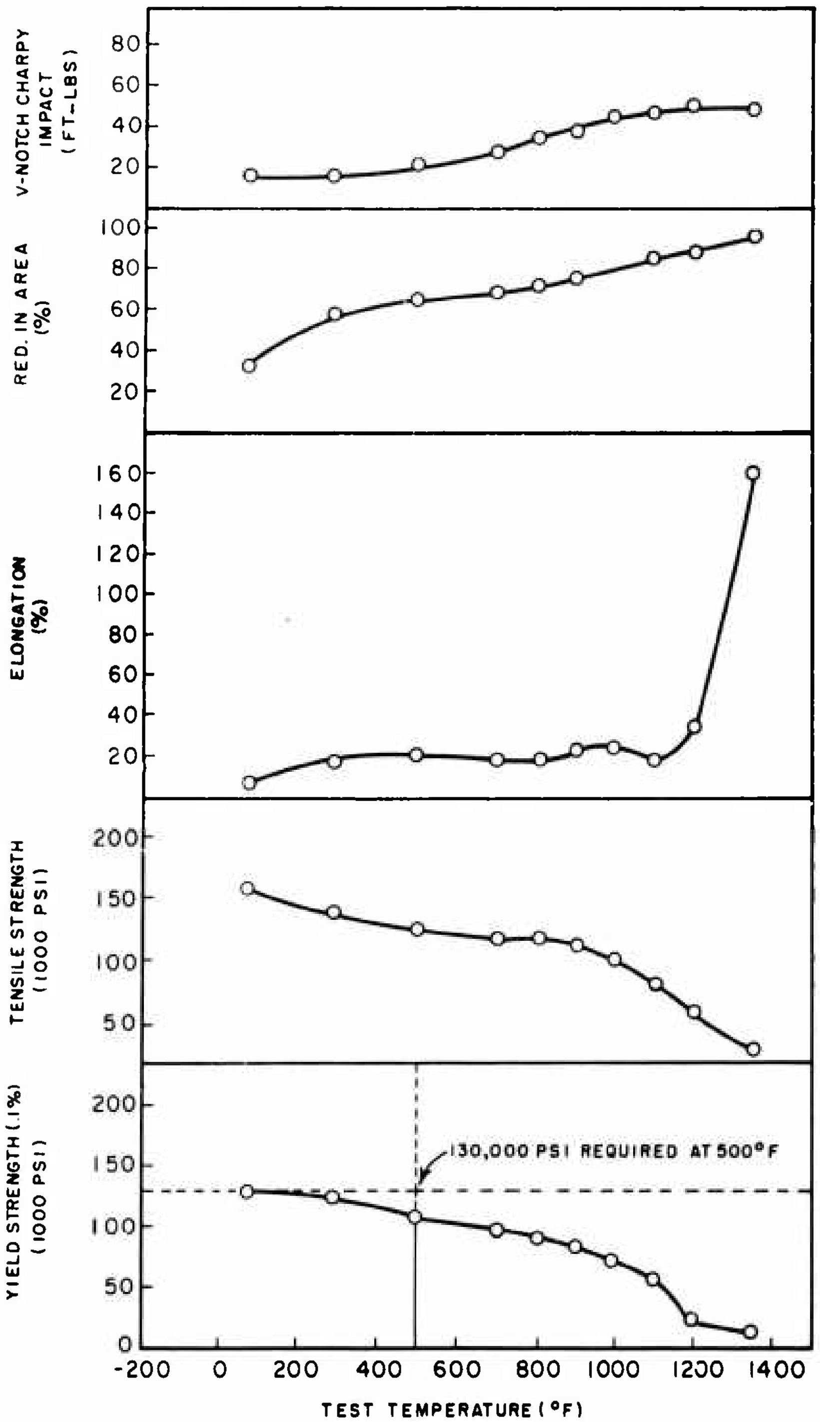


MECHANICAL PROPERTIES OF Ti-155A ALLOY
HEAT NO. 8780

HEAT TREATMENT { 1660 – 1½ HR. – W.Q. SOLUTION; 1100 – 4 HR. – A.C. AGING }

19-066-731/ORD-60 FIGURE 2 WAL-PMB APRIL 6, 1960

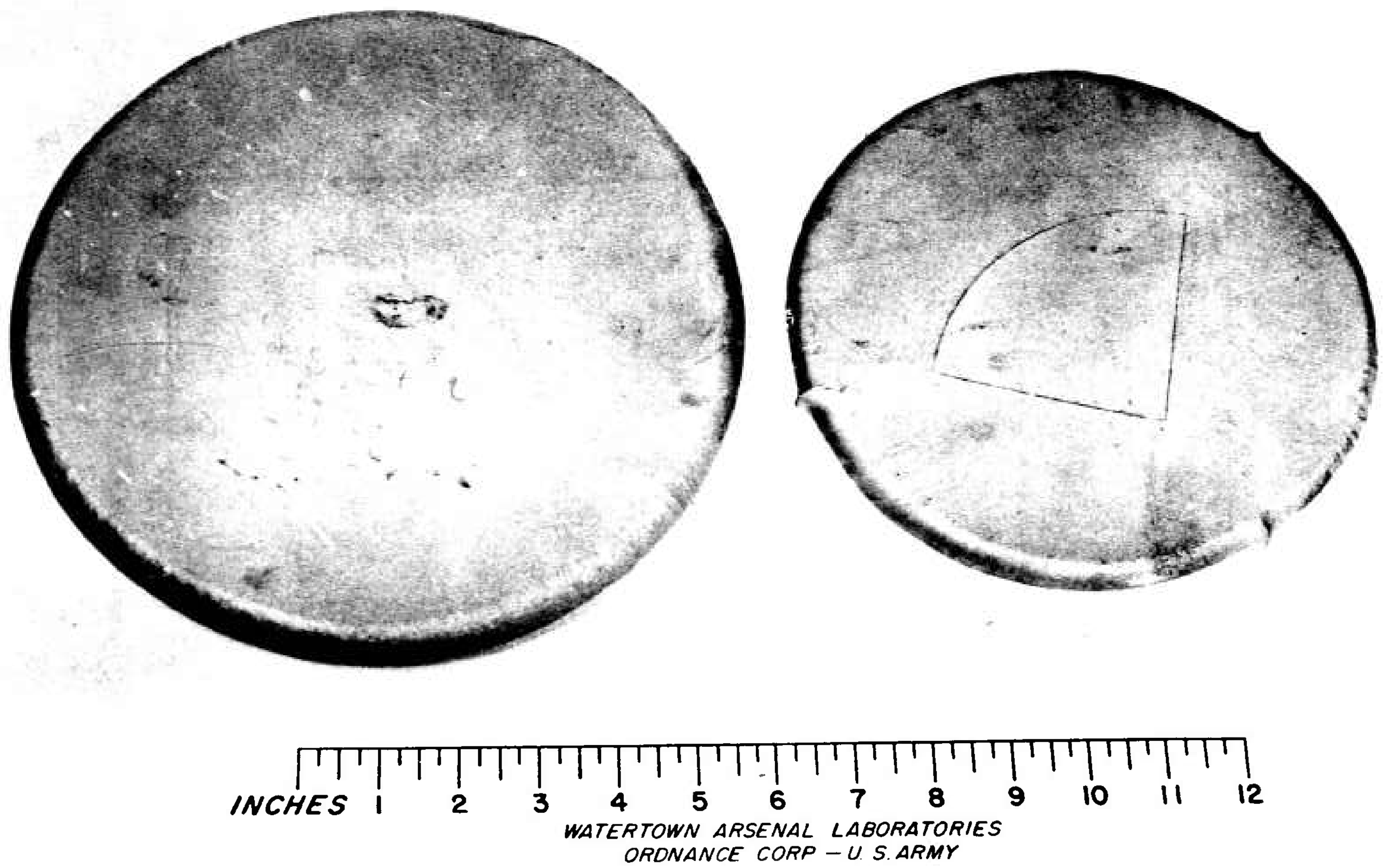
RATE OF LOADING { 30,000 P.S.I. PER MIN UP TO YS AT .2% OFFSET
60,000 P.S.I. PER MIN. ABOVE YS AT .2% OFFSET }



SHORT TIME ELEVATED TEMPERATURE TESTS

TIME AT TEMPERATURE — 20 MINUTES
6AL-4V Ti - ALLOY HT. NO. L-1122R-160 BHN SPONGE
4 1/2" BARSTOCK PRESS-FORGED TO 3/4" PLATE
HEAT TREATMENT - 1750°F 1HR.-W.Q. 1050°F-2HRS.-A.C.

19-066-733/ORD-60 FIGURE 3 WAL - PMB APRIL 6, 1960



UPSET DISCS [OPEN DIES]

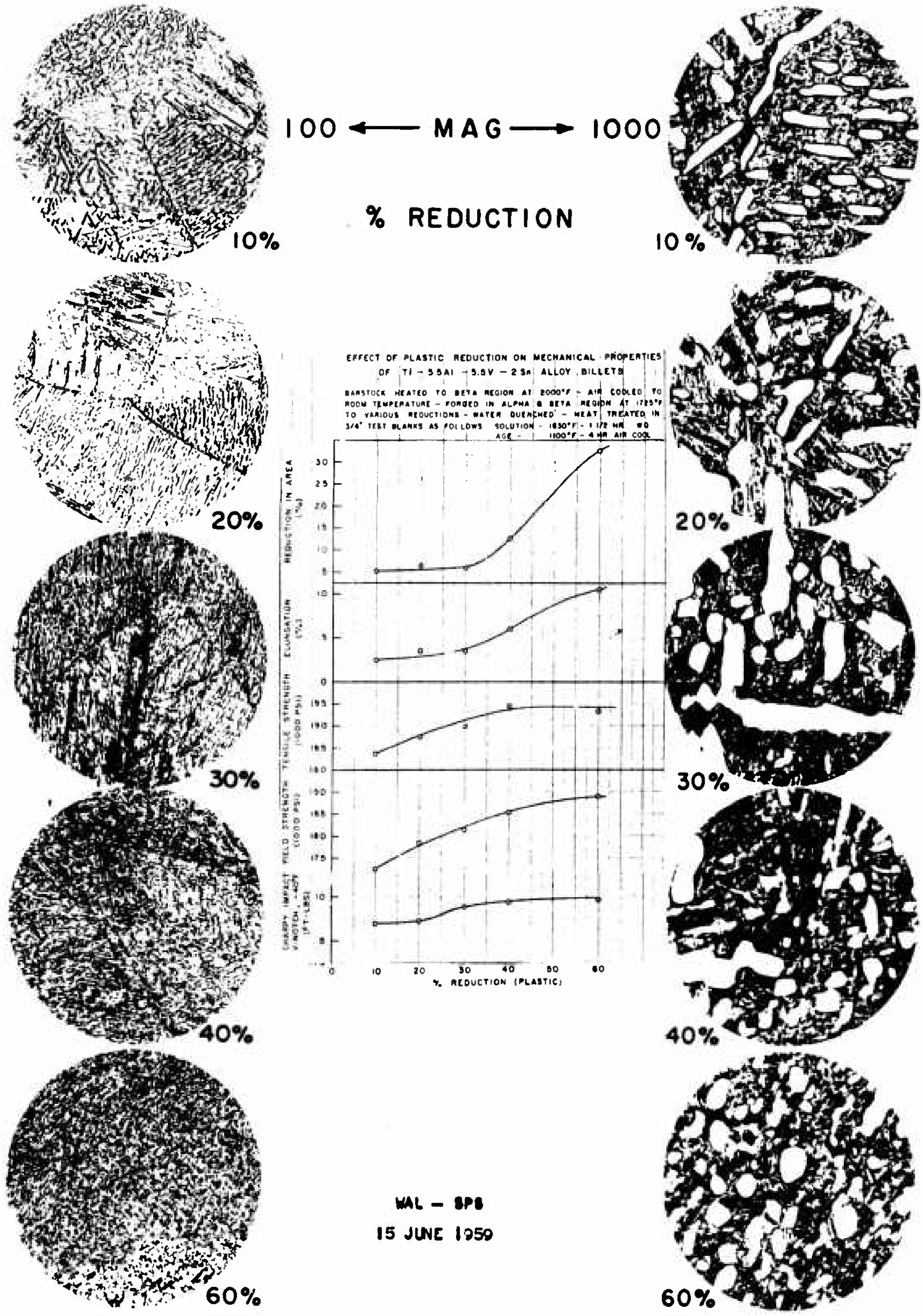
$1\frac{1}{2}$" THICK $\frac{3}{4}$" THICK

WATERTOWN ARSENAL LABORATORIES

19-066-710/ORD-60

APRIL 6, 1960

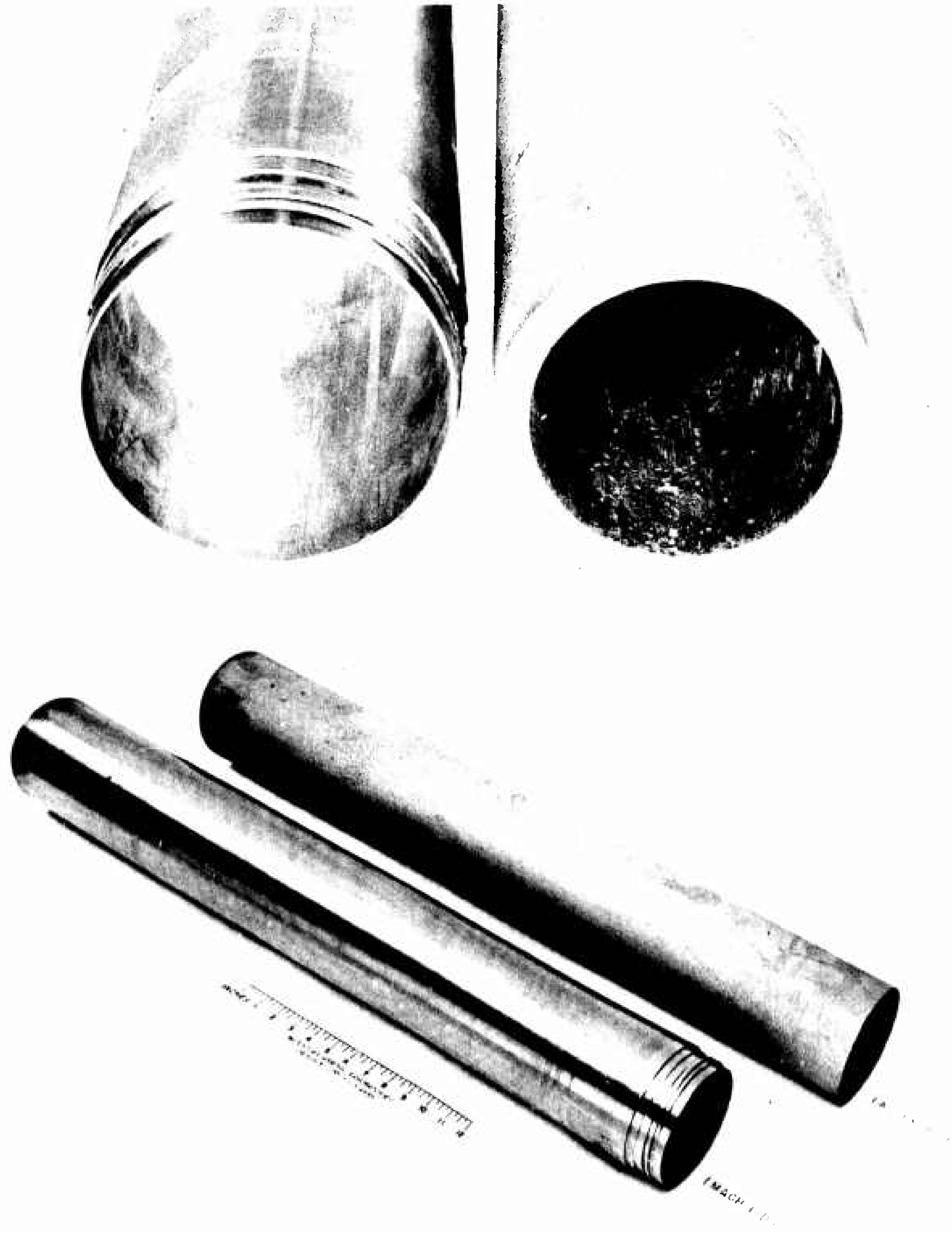
FIGURE 4



EFFECT OF PLASTIC REDUCTION ON STRUCTURE AND MECHANICAL PROPERTIES

Wtn. 639-17,089

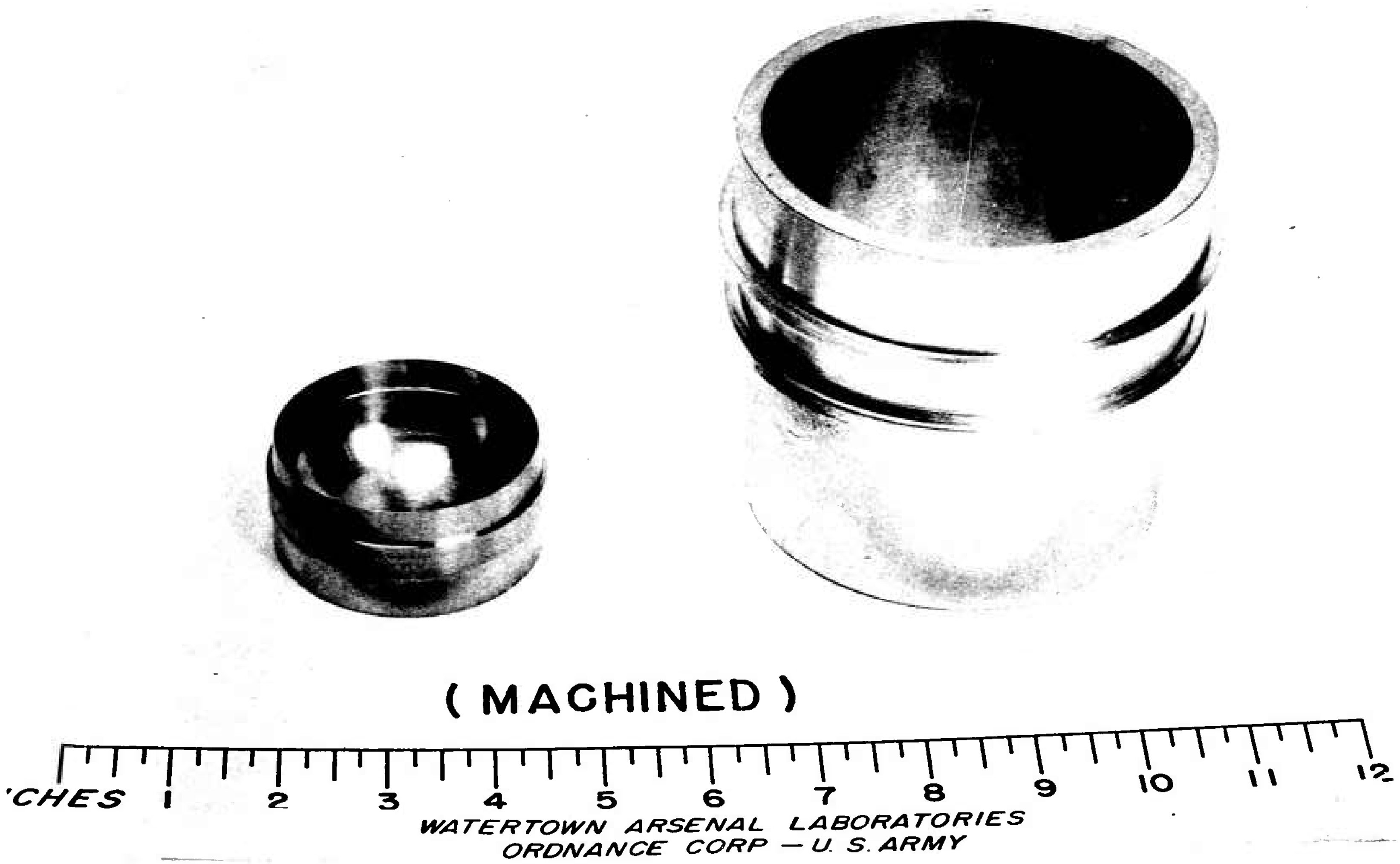
FIGURE 5



63-B [FORWARD EXTRUSION]   605 [FORWARD EXTRUSION]

WATERTOWN ARSENAL LABORATORIES

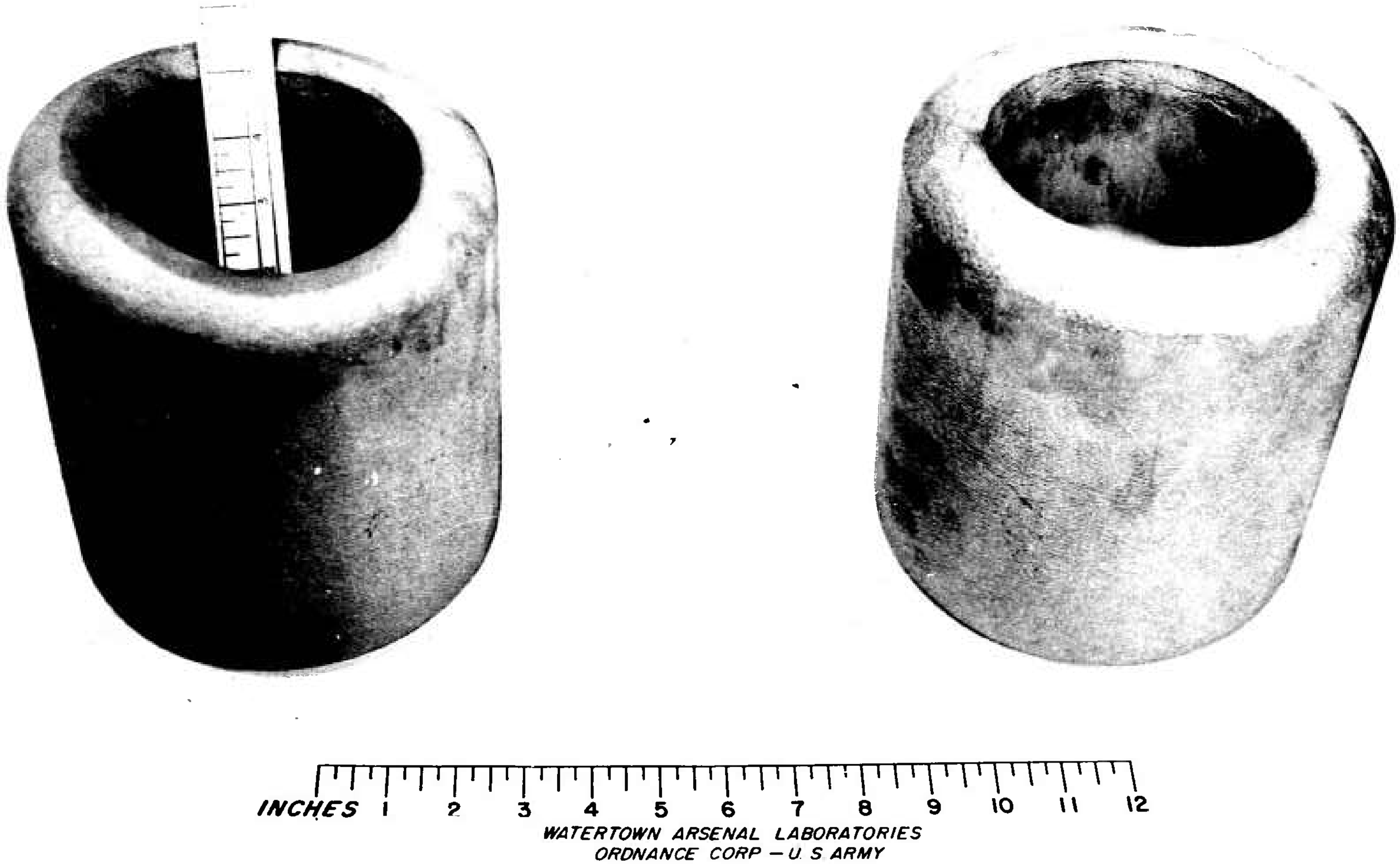
19-066-715/ORD-60   APRIL 6, 1960   FIGURE 6



DE-2 [CLOSED DIE FORGING] 606 [FORWARD EXTRUSION]

WATERTOWN ARSENAL LABORATORIES

19-066-712/ORD-60 APRIL 6, 1960 FIGURE 7



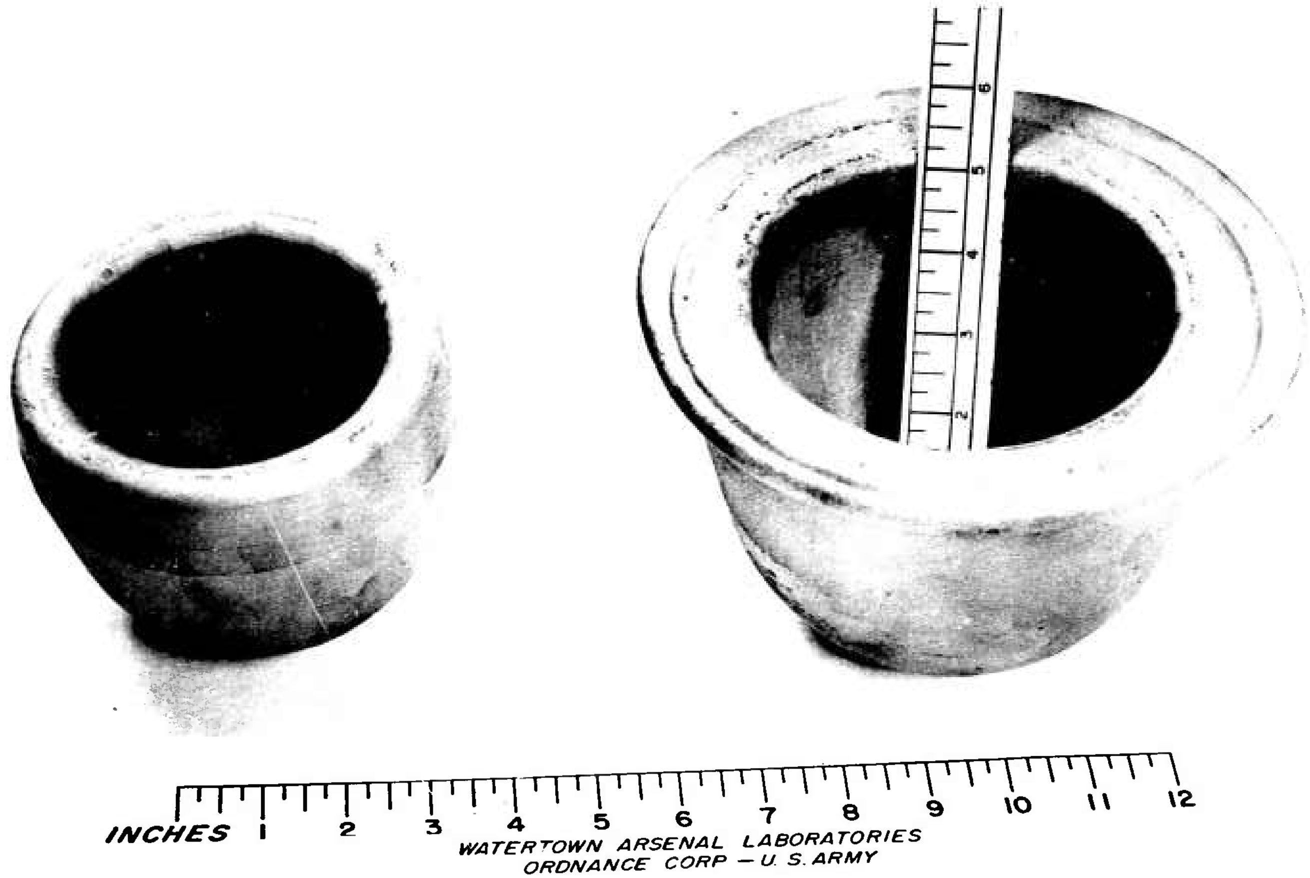
121 [REVERSE EXTRUSION]   119 [REVERSE EXTRUSION]

WATERTOWN ARSENAL LABORATORIES

APRIL 6, 1960

FIGURE 8

19-066-711/ORD-60



604 [CLOSED DIE FORGING] 680 [CLOSED DIE FORGING]

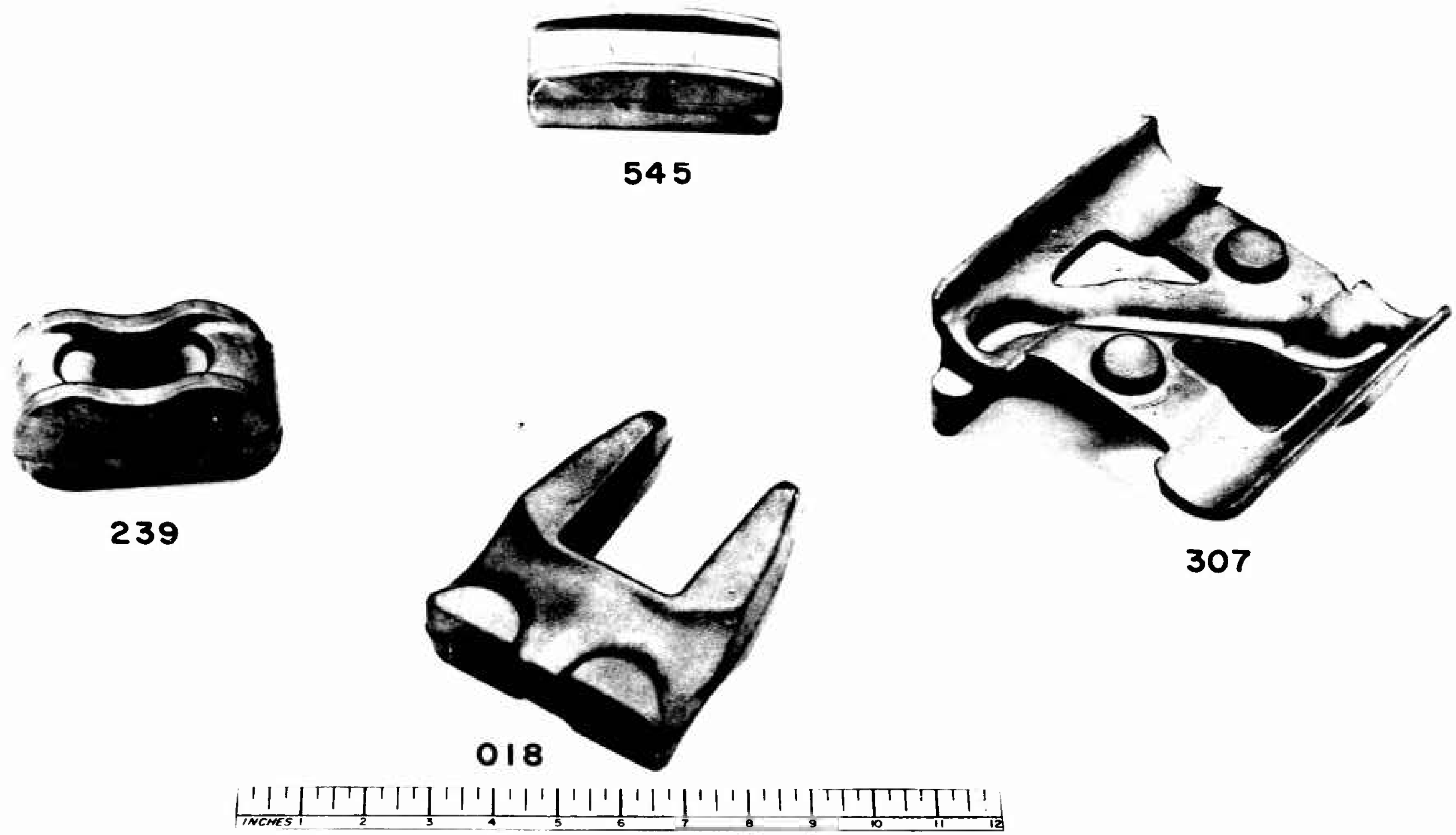
WATERTOWN ARSENAL LABORATORIES

19-066-709/ORD-60 APRIL 6, 1960 FIGURE 9

63-C [FORWARD EXTRUSION & EXPANSION]   63-N [REVERSE EXTRUSION]

WATERTOWN ARSENAL LABORATORIES

19-066-717/ORD-60   APRIL 6, 1960   FIGURE 10



545

239 [CLOSED DIE FORGINGS] 307

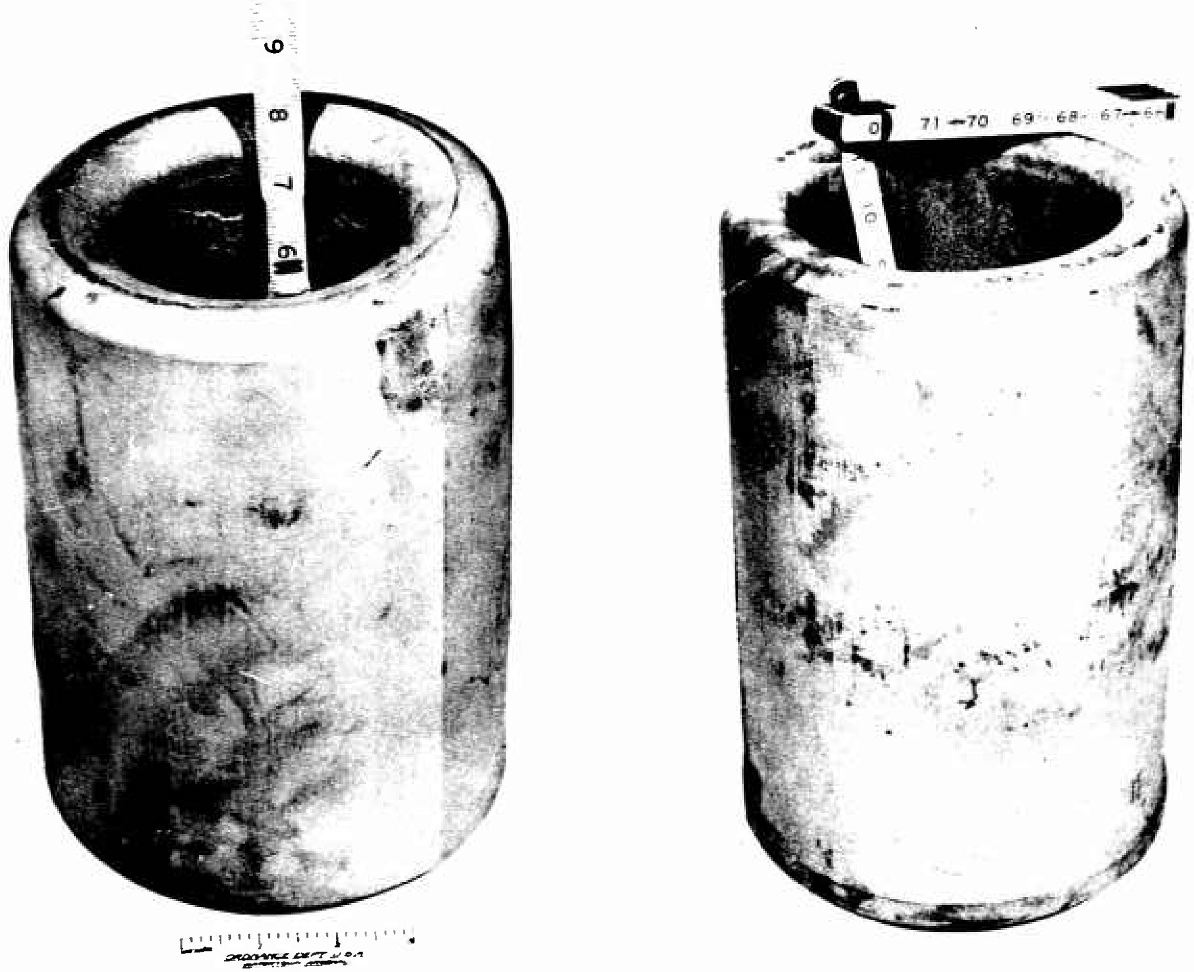
018

WATERTOWN ARSENAL LABORATORIES

W.T.N. 681-1216

APRIL 6, 1960

FIGURE 11



[REVERSE EXTRUSIONS]

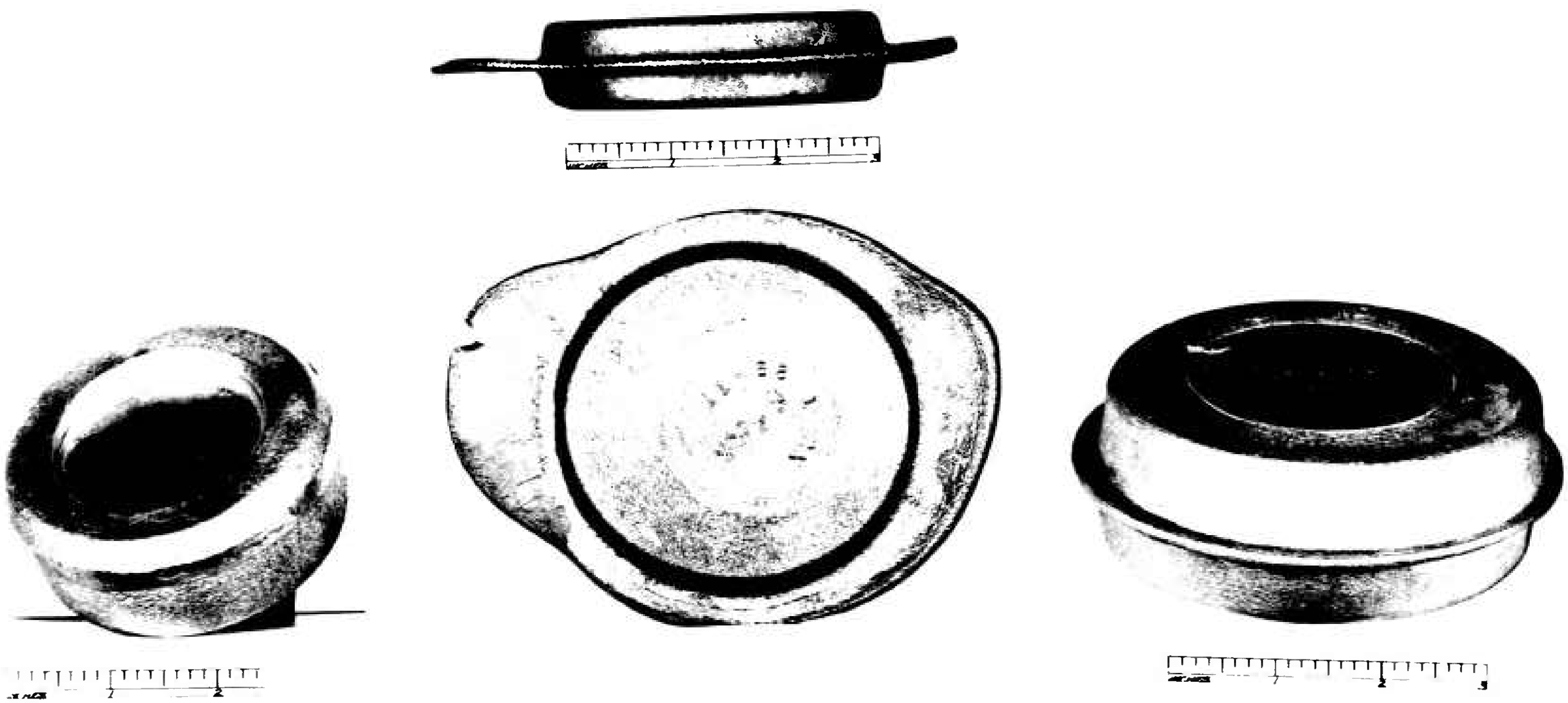
586 163

WATERTOWN ARSENAL LABORATORIES

19-066-714/ORD-60

APRIL 6, 1960

FIGURE 12



[CLOSED DIE FORGINGS]

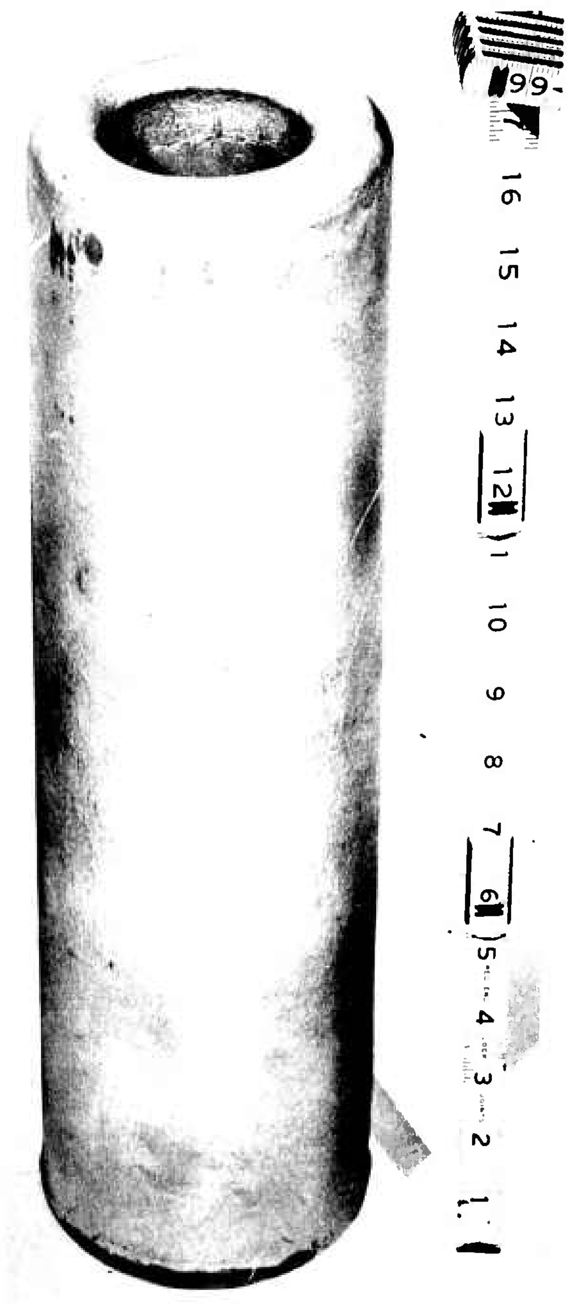
127 141 144

WATERTOWN ARSENAL LABORATORIES

APRIL 6, 1960

19-066-716/ORD-60

FIGURE 13



[REVERSE EXTRUSION]

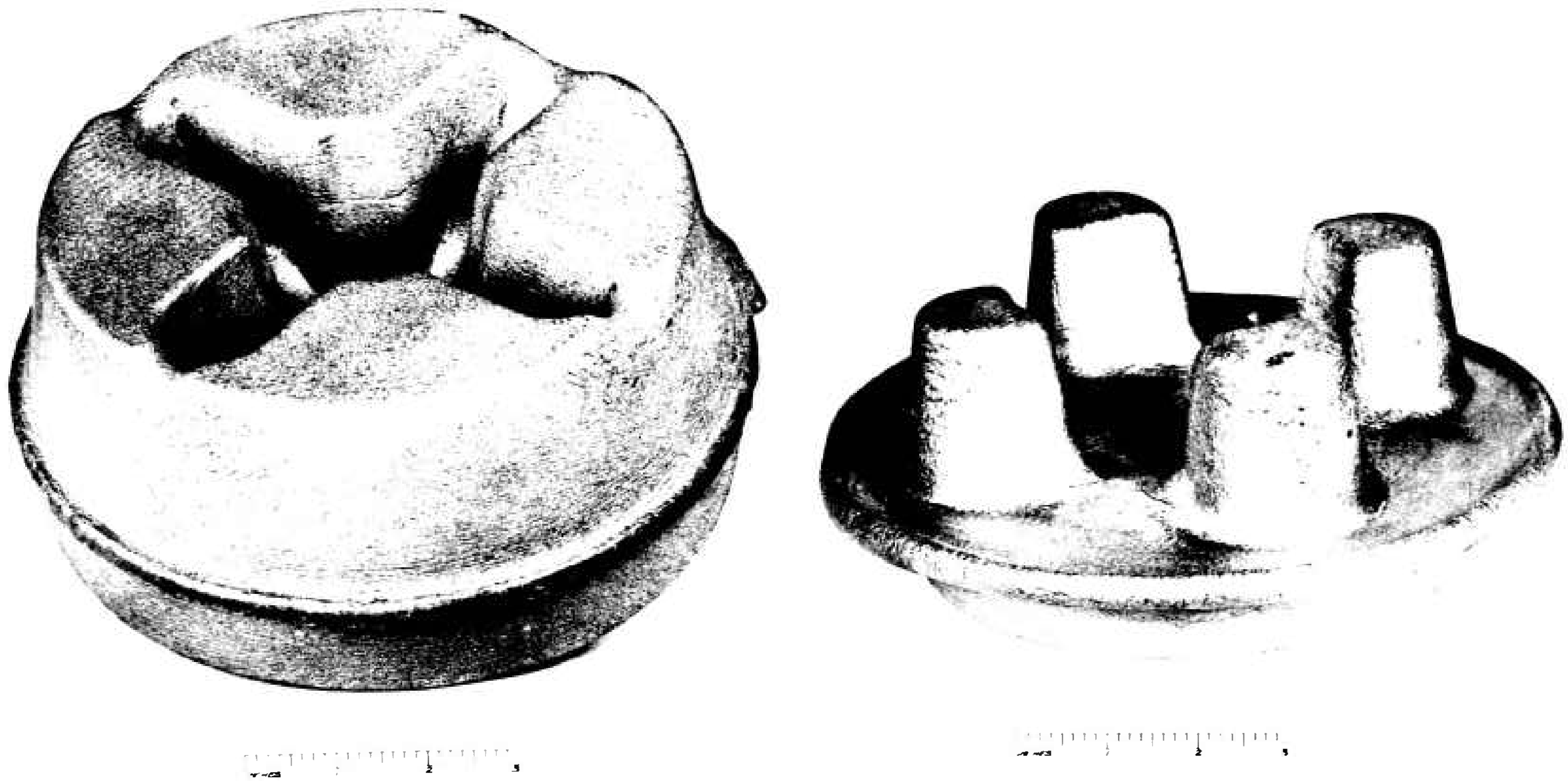
166

WATERTOWN ARSENAL LABORATORIES

APRIL 6, 1960

WTN. 224-1782

FIGURE 14



[CLOSED DIE FORGINGS]

142 153

WATERTOWN ARSENAL LABORATORIES

19-066-713/ORD-60 APRIL 6, 1960 FIGURE 15

MILITARY SPECIFICATION

TITANIUM ALLOY, WROUGHT, RODS, BARS AND BILLETS
(For Critical Applications)

1. SCOPE

1.1 Scope. - This specification covers wrought titanium alloy rods, bars, and billets for use in high-strength components for critical applications (see 6.1).

1.2 Form, finish, and condition. - Unless otherwise specified, the titanium alloy shall be furnished round, rough turned and, at the option of the contractor, in the annealed or heat-treated condition (see 6.2b).

2. APPLICABLE DOCUMENTS

2.1 The following documents of the issue in effect on date of invitation for bids, form a part of this specification:

STANDARDS

FEDERAL

FED. TEST METHOD STD. NO. 151 - Metals; Test Methods

FED-STD-184 - Identification Marking of Aluminum, Magnesium, and Titanium

MILITARY

MIL-STD-129 - Marking for Shipment and Storage

(Copies of specifications, standards, drawings, and publications required by contractors in connection with specific procurement functions should be obtained from the procuring activity or as directed by the contracting officer.)

2.2 Other publications. - The following documents form a part of this specification. Unless otherwise indicated, the issue in effect on date of invitation for bids shall apply.

AMERICAN SOCIETY FOR TESTING MATERIALS

ASTM Designation: B311-58 - Standard Method of Test for Density of Cemented Carbides

FSC 9530

ASTM Methods for Chemical Analysis of Metals

(Application for copies should be addressed to the American Society for Testing Materials, 1916 Race Street, Philadelphia 3, Pennsylvania.)

3. REQUIREMENTS

3.1 Chemical composition. - Unless otherwise specified in the contract or order, the chemical composition of the titanium alloys shall comply with the range proposed by the contractor. The contractor shall submit a certified analysis of each heat to the procuring agency. The statement of analysis shall include all elements intentionally added as well as the amounts of carbon, oxygen, hydrogen, and nitrogen present as impurities, and in any case, the amounts of iron and copper shall be reported. Unless otherwise specified, the carbon content of the material furnished shall not exceed 0.05 percent, the oxygen content shall not exceed 0.19 percent, the hydrogen content shall not exceed 0.010 percent and the nitrogen content shall not exceed 0.04 percent.

3.2 Heat treatment. - When material is heat treated to meet the applicable mechanical property requirements of this specification, the details of the heat treating procedure shall be provided by the contractor and shall be forwarded with each lot at the time of shipment.

3.3 Mechanical properties.

3.3.1 Tensile properties.

3.3.1.1 Yield strength. - The yield strength range shall be as specified in the contract or order.

3.3.1.1.1 Maximum yield strength. - The specified yield-strength range may be exceeded providing the percent elongation, percent reduction of area, and V-notched Charpy impact resistance do not fall below the values specified in table I for the upper limit of the specified yield-strength range.

3.3.1.2 Ductility. - The reduction of area and elongation shall be as specified in table I for the applicable yield strength range.

3.3.2 Impact resistance. - The V-notched Charpy impact resistance shall be as specified in table I for the applicable yield strength range.

3.3.3 Density. - The maximum density of the titanium alloy shall be 4.70 grams per cubic centimeter. Certification of the density shall be provided by the contractor.

3.4 Dimensions and dimensional tolerances. - Dimensions and dimensional tolerances shall be as specified in the contract or order.

3.5 Identification marking. - Unless otherwise specified, identification marking shall be in accordance with Standard FED-STD-184.

Table I - Minimum mechanical property requirements

Yield strength (0.1% offset)	Average elongation 1/	Average reduction of area	Average V-notched Charpy impact resistance at -40°F
psi	percent	percent	ft.-lbs.
120,000 - 129,999	14	29	15
130,000 - 139,999	12	26	12
140,000 - 149,999	11	23	11
150,000 - 159,999	10	21	10
160,000 - 169,999	8	18	8
170,000 - 179,999	8	18	8
180,000 - 189,999	7	16	7
190,000 - 199,999	7	14	7
200,000 - 210,000	6	13	6

1/ Bars or billets having a diameter of greater than 2 inches shall meet the additional requirement that in the "as-received" (mill annealed) condition, the elongation, as measured on a transverse tensile specimen located at least one inch from the surface, shall be a minimum of 8 percent. Results of this test, including yield strength and tensile strength readings, shall be forwarded to the procuring activity.

3.6 Workmanship. - The titanium alloys shall be uniform in quality and condition and shall be free from seams, cracks, laminations, inclusions, hard spots, and other defects which would detrimentally affect the fabricability or serviceability of the material.

4. QUALITY ASSURANCE PROVISIONS

4.1 General quality assurance provisions.

4.1.1 Unless otherwise specified herein, the supplier is responsible for the performance of all inspection requirements prior to submission for Government inspection and acceptance. Except as otherwise specified, the supplier may utilize his own facilities or any commercial laboratory acceptable to the Government. Inspection records of the examinations and tests shall be kept complete and available to the Government as specified in the contract or order.

4.1.2 Government surveillance. - At the option of the procuring activity, the contractor will be subject to verification testing as prescribed in 4.5.2.1.1, 4.5.2.1.2, 4.5.2.1.3, and 4.5.2.1.4.

4.2 Lot. - Unless otherwise specified in the contract or order, a lot shall consist of all rods, bars, or billets submitted for inspection at the same time, of the same heat, the same condition, and the same diameter. When heat treated, a lot shall be of the same processing cycle and heat treated at the same time in a batch furnace, or passed consecutively through a continuous type of heat-treating process.

4.3 Sampling.

4.3.1 For chemical analysis. - At least one sample for chemical analysis shall be selected from each heat in accordance with method 111 or method 112 of Fed. Test Method Std. No. 151.

4.3.2 For mechanical properties. - Except when sampling plans for mechanical properties tests are specified in the contract or order, the following sampling procedures shall be used:

4.3.2.1 For rods or bars having a diameter equal to or greater than 1/4 inch but less than 1 3/4 inches, one sample of sufficient length to obtain and prepare specimens as described in 4.5.2.1.1 shall be selected from each 500 pounds of material, comprising the lot.

4.3.2.1.1 For government verification tests. - In addition to the sampling required in 4.3.2.1, a like sample shall, at the option of the procuring activity, be selected, prepared as shown in 4.5.2.1.1, and forwarded to the procuring activity for verification testing.

4.3.2.2 For bars or billets having a diameter equal to or greater than 1 3/4 inches but less than 5 inches, one 5-inch length shall be selected from each 500 pounds of material, comprising the lot.

4.3.2.2.1 For government verification tests. - In addition to the sampling required in 4.3.2.2, two additional samples shall, at the option of the procuring activity, be selected, prepared as shown in 4.5.2.1.2, and forwarded to the procuring activity for verification testing.

4.3.2.3 For bars or billets having a diameter equal to or greater than 5 inches but less than 10 inches, one 5-inch length shall be selected from each 1,000 pounds, comprising the lot, and prepared in accordance with 4.5.2.1.3.

4.3.2.4 For billets having a diameter equal to or greater than 10 inches, one 2-inch thick sample representing the entire cross section shall be selected from each 1,000 pounds, comprising the lot, and prepared in accordance with 4.5.2.1.4.

4.4 Examination.

4.4.1 Visual. - All material shall be subject to visual examination for compliance with identification marking (see 3.5) and workmanship requirements (see 3.6).

4.4.2 Dimensional. - All material shall be subject to examination for compliance with dimensional requirements (see 3.4).

4.4.3 Preparation for shipment. - Examination shall be made to determine compliance with the requirements for the preparation for shipment (see section 5).

4.5 Tests.

4.5.1 Chemical analysis. - Samples for chemical analysis shall be prepared and tested in accordance with method 111 or method 112 of Fed. Test Method Std. No. 151. In case of dispute, the analysis by method 111 shall be the basis for acceptance or rejection.

4.5.1.1 Determination of oxygen (and hydrogen). - Oxygen shall be determined using (a) Vacuum Fusion Method by the Walter (dry-crucible) technique or (b) Vacuum Fusion Method by Platinum-Flux Technique (see methods 1 and 2 in the appendix to this specification).

4.5.1.2 Determination of oxygen. - Oxygen may be determined by separate analysis by methods 1 or 2 (see 4.5.1.1) or by the Inert-Gas Fusion Method (see method 3 in the appendix).

4.5.1.3 Determination of hydrogen. - When hydrogen is to be determined by separate analysis, the Hot Extraction Method, or an equivalent method, shall be used (see method 4 in the appendix).

4.5.1.4 Determination of nitrogen. - Nitrogen shall be determined by ASTM Method E120-56, "Chemical Analysis of Titanium and Titanium-Base Alloys", or any other applicable ASTM method.

4.5.1.5 Determination of carbon. - Carbon shall be determined by either the High-Frequency Furnace Combustion Method (see method 5 in the appendix) or the Tube Furnace Combustion Method (see method 6 of the appendix).

4.5.2 Mechanical properties tests.

4.5.2.1 Preparation of samples.

4.5.2.1.1 For rods or bars of diameters from 1/4 inch up to 1 3/4 inches. - Samples shall be heat treated to obtain the required mechanical properties, machined to obtain at least two longitudinal V-notched Charpy impact test specimens and two longitudinal tensile test specimens in accordance with methods 221 and 211 of Fed. Test Method Std. No. 151. Tensile test specimens shall be type R4 for diameters of 1/4 up to 3/8 inch, type R3 for diameters of 3/8 inch up to 1/2 inch, and type R2 for diameters of 1/2 up to 1 3/4 inches.

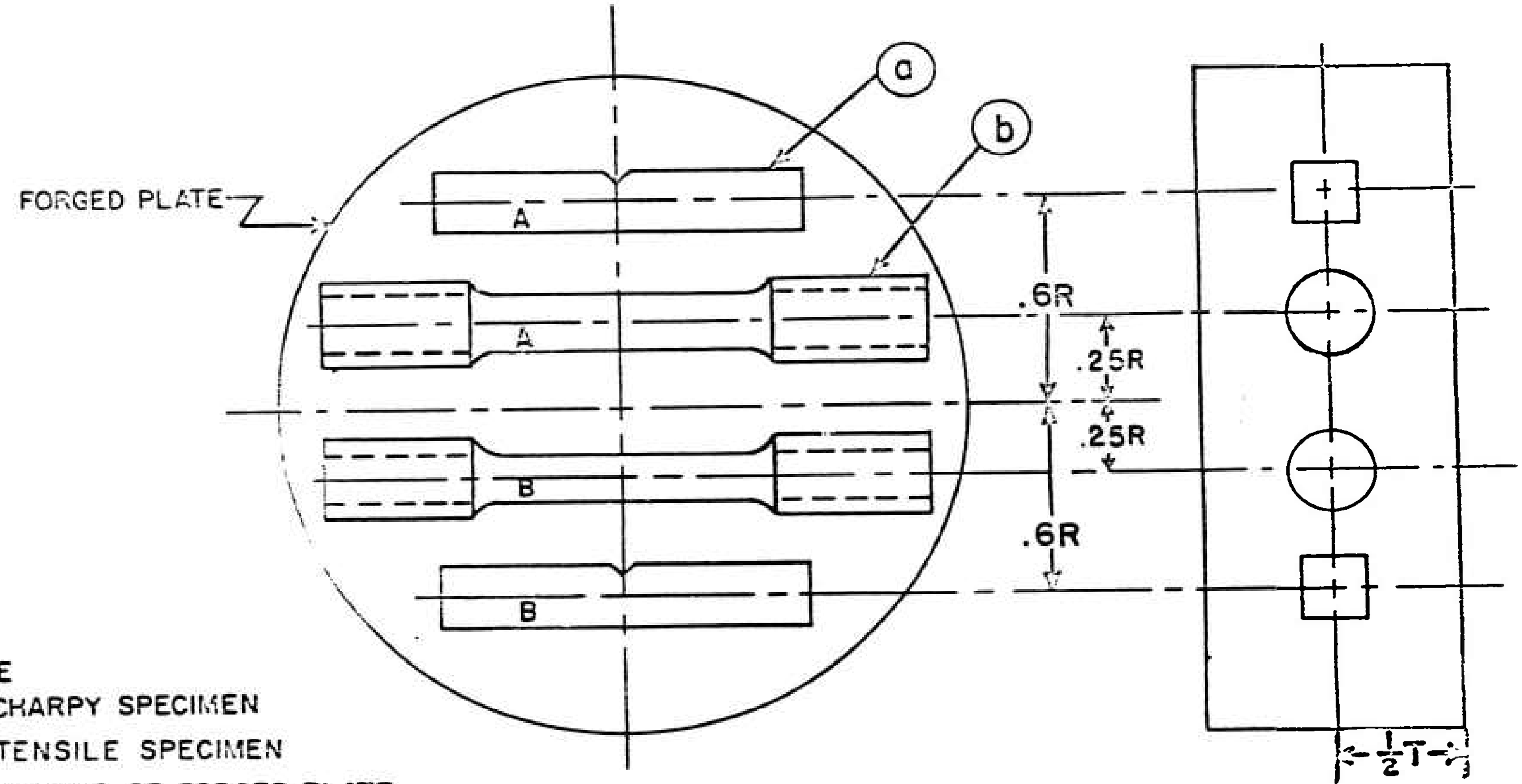
4.5.2.1.2 For bars or billets of diameters from 1 3/4 inches up to 5 inches. - Unless otherwise specified, samples shall be upset forged in the longitudinal direction (at a temperature of 75°F below the beta transus (see 6.4.1) for the particular alloy being used) to a plate of thickness shown in table II for the applicable yield strength range (see 6.2k). The plate shall be heat treated to obtain the required mechanical properties and shall be machined to obtain test specimens as shown in figure 1. At the option of the procuring activity, a second forged and heat-treated plate and a third forged but unheat-treated plate shall be forwarded to the procuring activity for verification testing. Tensile test specimens shall be the R3 type shown in method 211 of Fed. Test Method Std. No. 151 for diameters of rods or bars of 1 3/4 inches up to 2 1/2 inches and the R2 type for diameters of 2 1/2 inches up to 5 inches.

Table II - Minimum thickness of forged test plates.

For yield strength range	Thickness of plate (inches)
psi	
120,000 - 129,999	2
130,000 - 149,999	1 1/2
150,000 - 169,999	1
170,000 - 210,000	3/4

4.5.2.1.3 For bars or billets of diameters from 5 inches up to 10 inches. - Samples shall be quartered. Unless otherwise specified, one of the quarters shall then be upset forged to a plate of thickness shown in table II for the applicable yield strength range (see 6.2k), heat treated to obtain the required mechanical properties, and machined to obtain test specimens as shown in figure 1. At the option of the procuring activity, a second quarter which has been upset forged and heat treated, a third quarter which has been upset forged but not heat treated, and the fourth quarter which has not been forged or heat treated shall be forwarded to the procuring activity for verification testing. Tensile test specimens shall be the R2 type shown in method 211 of Fed. Test Method Std. No. 151.

4.5.2.1.4 For billets of diameters 10 inches and over. - Samples shall be quartered and machined into rectangular shape 4 inches high. Unless otherwise specified, one quarter shall be upset forged in a radial direction to a plate thickness shown in table II for the applicable yield strength range (see 6.2k), heat treated to obtain the required mechanical properties, and machined to obtain test specimens as shown in figure 1. At the option of the procuring activity, a second quarter which has been upset forged and heat treated, a third quarter which has been upset forged but not heat treated, and the fourth quarter section which has not been forged or heat treated shall be forwarded to the procuring activity for verification testing. Tensile specimens shall be the R2 type shown in method 211 of Fed. Test Method Std. No. 151.



NOTE
(a) CHARPY SPECIMEN
(b) TENSILE SPECIMEN
R = RADIUS OF FORGED PLATE
A & B - SPECIMEN IDENTIFICATION

FIGURE 1

LOCATION OF TEST SPECIMENS IN FORGED PLATE

4.5.2.2 Tension tests. - Unless otherwise specified, at least two tensile test specimens shall be prepared and tested in accordance with method 211 of Fed. Test Method Std. No. 151. The yield strength shall be determined by the offset method by plotting a stress-strain diagram. The limiting offset shall be 0.10 percent (0.001 inch per inch of gage length). The strain rate shall not exceed 0.005 in./in./min. up to the yield strength at 0.2 percent offset.

4.5.2.2.1 Yield strength. - If the average yield strength for all specimens tested is above the minimum yield strength requirements, specified in the contract or order, the lot represented will be accepted as having met the requirements for yield strength.

4.5.2.2.2 Ductility. - The reduction of area and elongation shall be the average of all determinations obtained from tests made in connection with the inspection of a lot of material.

4.5.2.3 Impact tests. - Unless otherwise specified, at least two standard Charpy V-notch impact test specimens shall be prepared and tested in accordance with method 221 of Fed. Test Method Std. No. 151. When a standard size impact specimen can not be obtained, the contractor, at the option of the contracting officer, may be required to demonstrate, by special tests prescribed by the contracting officer and agreed to by the contractor, that the material he proposes to furnish is satisfactory insofar as impact resistance is concerned. The temperature of the test specimen at the time of fracture shall be -40°F ± 2°F. The error in the Charpy machine shall not exceed ± 1 ft.-lb. for energy values up to 20 ft.-lbs. or ± 5 percent for energy values over 20 ft.-lbs. when the machine is tested using comparison specimens prepared by Watertown Arsenal (see 6.3). This comparison shall have been made within one year prior to the time of inspection testing.

4.5.2.3.1 Impact resistance. - If the average value for all samples tested is equal to or above the value given in table I opposite the upper limit of the required yield strength range, the lot will be accepted as having met the requirements for impact resistance.

4.5.2.4 Density tests. - When required, density tests shall be performed in accordance with ASTM Designation B311-58. Specimens for this test may be taken from mechanical test samples.

4.6 Rejection and retests or resubmittal. - Rejection and retests or resubmittal of rejected lots shall be in accordance with the general section of Fed. Test Method Std. No. 151.

5. PREPARATION FOR DELIVERY

5.1 Preservation and packaging

5.1.1 Level C. - Cleaning, drying, preservation, and packaging shall be in accordance with the manufacturer's commercial practice.

5.2 Packing

5.2.1 Level C. - Packing shall be in accordance with commercial practice adequate to insure acceptance and safe delivery by the carrier for the mode of transportation employed.

5.3 Marking. - In addition to any special marking required by the contract or order, shipments shall be marked in accordance with the requirements of Standard MIL-STD-129.

6. NOTES

6.1 Intended use. - This specification covers material which is suitable for processing by hot forming and heat treatment or by heat treatment only, or for direct application to highly stressed critical components, and it is required for use with Specification MIL-T-46035.

6.2 Ordering data. - Procurement documents should specify the following:

(a) Title, number, and date of this specification.

(b) Form and condition, if necessary (see 1.2).

(c) Chemical analysis when stipulated (see 3.1).

(d) Yield strength range (see 3.3.1.1).

(e) Dimensions and dimensional tolerances (see 3.4).

(f) Special identification marking not covered in 3.5.

(g) Name of inspecting agency when inspection shall be performed by other than contractor (see 4.1.1).

(h) Lot size if not as specified in 4.2.

(i) When special sampling plans for mechanical properties are to be used (see 4.3.2).

(j) Whether or not contractor should forward material to procuring activity for verification testing (see 4.5.2.1.1, 4.5.2.1.2, 4.5.2.1.3, and 4.5.2.1.4).

(k) When minimum thickness of forged test plates shall differ from table II (see 4.5.2.1.2, 4.5.2.1.3, and 4.5.2.1.4).

(l) When density tests are required and frequency of testing (see 4.5.2.4).

(m) When special marking-for-shipment requirements are necessary (see 5.3).

6.3 Information regarding comparison tests on Charpy impact machines employing Watertown Arsenal comparison specimens can be obtained from the local Ordnance District or from the Commanding Officer, Watertown Arsenal, Watertown 72, Massachusetts.

6.4 Definition.

6.4.1 Beta transus. - The Beta transus is the temperature which designates the phase boundary between the alpha-plus-beta and beta fields for a given alloy composition.

NOTICE: When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or the other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

Custodian:

Army - Ordnance Corps

Preparing Activity:

Army - Ordnance Corps

APPENDIX

...emical Test Methods for Impurities in Titanium.

Oxygen

Method 1: Determination of oxygen (and hydrogen) with the Vacuum-Fusion Method by the Walter (dry-crucible) Technique.

This method is as shown in Information Bulletin No. T8, Part II, issued by the Metallurgical Advisory Committee on Titanium, on pp. 28-43.

Method 2: Determination of oxygen (and hydrogen) by the Platinum-Flux Technique of Vacuum Fusion.

This method has been recommended by the Panel on Methods of Analysis and will be published by the Metallurgical Advisory Committee on Titanium and the ASTM. In the interim, the method may be obtained from the Watertown Arsenal Laboratories.

Method 3: Determination of oxygen by the Inert-Gas Fusion Method.

This method has been recommended by the Task Force on Oxygen, and is being processed for submission to the Panel on Methods of Analysis. In the interim, information on the method may be obtained from the Watertown Arsenal Laboratories, or from the manufacturer of the equipment, Laboratory Equipment Corporation, St. Joseph, Michigan.

Hydrogen

Method 4: Determination of hydrogen by the Hot Extraction Method.

Suitable equipment and procedures have been developed by National Research Corporation, Cambridge, Massachusetts, and Fisher Scientific Company, Chicago, Illinois. Other equipment and procedures may be used if acceptable to the procuring agency.

Carbon

Method 5: Determination of carbon by the High Frequency Furnace Combustion Method.

This method is shown in Information Bulletin No. T8, Part II, issued by the Metallurgical Advisory Committee on Titanium, on pp. 12-19.

Method 6: Determination of Carbon by the Tube Furnace Combustion Method.

This method is shown in Information Bulletin No. T8, Part II, issued by the Metallurgical Advisory Committee on Titanium, on pp. 7-11.

MILITARY SPECIFICATION

TITANIUM ALLOY; HIGH-STRENGTH WROUGHT (For Critical Components)

1. SCOPE

1.1 This specification covers high-strength wrought titanium alloys, in annealed or heat-treated shapes, having a critical section thickness of one-quarter to two and one-half inches, for critical components other than armor, such as tubes, chambers, and nozzles (see 6.2.1).

2. APPLICABLE DOCUMENTS

2.1 The following documents of the issue in effect on date of invitation for bids form a part of this specification.

SPECIFICATIONS

MILITARY

MIL-T-46038 - Titanium Alloy; Wrought, Rods, Bars and Billets (for Critical Applications)

STANDARDS

FEDERAL

FED. TEST METHOD STD. NO. 151 - Metals; Test Methods

MILITARY

MIL-STD-129 - Marking for Shipment and Storage

(Copies of specifications, standards, drawings, and publications required by contractors in connection with specific procurement functions should be obtained from the procuring activity or as directed by the contracting officer).

2.2 Other publications. - The following documents form a part of this specification. Unless otherwise indicated, the issue in effect on date of invitation for bids shall apply.

AMERICAN SOCIETY FOR TESTING MATERIALS

ASTM Designation: B311-58 - Standard Method of Test for Density of Cemented Carbides.

ASTM Designation: E21-58T Tentative Recommended Practice for Short-Time Elevated-Temperature Tension Tests of Materials.

(Application for copies should be addressed to the American Society for Testing Materials, 1916 Race Street, Philadelphia 3, Pennsylvania.)

3. REQUIREMENTS

3.1 Materials. - Bars and billets used in fabricating the wrought products covered by this specification shall comply with the requirements of Specification MIL-T-46038.

3.2 Hydrogen. - The hydrogen content of the products furnished shall not exceed 0.0125 percent.

3.3 Processing controls.

3.3.1 Welding. - Components shall not be welded, except on prolongations. All welds shall be so located that they will not affect the finished components or the test metal.

3.3.2 Straightening. - The material shall not be straightened or worked after the final heat treatment operation.

3.4 Heat treatment. - Heat treatment, (solutionizing, cooling, stress-relieving, and aging) shall be performed uniformly on the material being processed. Unless otherwise specified, the quenching of tubular components shall be done vertically with the bore unobstructed, so as to permit free passage of the coolant through the bore. Aging shall be performed at a temperature of not less than 500°F, and for a sufficient time to insure uniform response throughout the section.

3.5 Mechanical properties.

3.5.1 Tensile properties.

3.5.1.1 Yield strength. - The yield strength shall be as specified in the contract, on the order, or on the applicable drawings.

3.5.1.1.1 Maximum yield strength. - The specified yield strength range may be exceeded providing the percent elongation, percent reduction in area, and V-notch Charpy impact resistance do not fall below values specified in table I for the upper limit of the specified yield strength range.

Table I - Minimum mechanical property requirements

Yield strength increments (0.1% offset)	Transverse direction: Average elongation	Average reduction in area	V-notch Charpy impact resistance (at -40°F)
psi	percent	percent	ft.-lbs.
120,000-129,999	11	24	11
130,000-139,999	10	20	10
140,000-149,999	9	16	9
150,000-159,999	8	15	8
160,000-169,999	7	14	7
170,000-179,999	6	13	6
180,000-189,999	6	13	6
190,000-199,999	5	12	5

3.5.1.1.2 Elevated temperature properties. - In addition to the above requirements, for applications requiring elevated temperature properties where room temperature yield strength requirements are at least 170,000 p.s.i., the contractor shall demonstrate, by presenting published data or conducting special tests, that the proposed alloy will meet a minimum transverse yield strength (0.1 percent offset) requirement of 130,000 p.s.i. at 500°F.

3.5.1.2 Ductility. - The reduction in area and elongation requirements shall be as specified in table I for the applicable yield strength range.

3.5.2 Impact resistance. - The V-notch Charpy impact resistance shall be as specified in table I for the applicable yield strength range.

3.6 Density. - The maximum density of titanium alloy shall be 4.70 grams per cubic centimeter. Certification of the density shall be provided by the contractor.

3.7 Dimensions. - Dimensions and dimensional tolerances shall be as specified on the applicable drawing, contract or order, plus any prolongation (see 6.2.2) which is an integral part of the piece as heat treated.

3.8 Identification marking. - Unless otherwise specified, each piece shall be legibly and indelibly marked with the piece number, heat number, or designation, the number of this specification, and the manufacturer's identification (see 6.1).

3.9 Workmanship. - The titanium alloys shall be uniform in quality and condition; free from seams, injurious segregations, cracks and other defects which, due to their nature, degree or extent, would detrimentally affect the suitability of the material for the intended use.

4. QUALITY ASSURANCE PROVISIONS

4.1 General quality assurance provisions.

4.1.1 Unless otherwise specified herein, the supplier is responsible for the performance of all inspection requirements prior to submission for Government inspection and acceptance. Except as otherwise specified, the supplier may utilize his own facilities or any commercial laboratory acceptable to the Government. Inspection records of the examinations and tests shall be kept complete and available to the Government, as specified in the contract or order.

4.1.2 Government surveillance. - Unless otherwise specified, the contractor will be subject to periodic, random checking of material ordered under this specification through comparison testing of mechanical properties by both Government and contractor (see 4.3.2.3 and 4.5.1.2.1.2). Not more than ten percent of the lots in the contract or order will be subjected to this comparison testing.

4.2 Lot. - A lot shall consist of all material of the same type and size, produced from the same heat, subjected to the same hot working process, and heat treated at the same time in a batch furnace, or that pass consecutively through a continuous type of heat-treating process.

4.3 Sampling.

4.3.1 For hydrogen analysis. - Unless otherwise specified, at least one sample for hydrogen analysis shall be selected from material representing each heat (see 4.5.1.1 and 6.1k).

4.3.2 For mechanical properties tests.

4.3.2.1 For closed and open die forgings. - Except when a sampling plan has been specified in the contract or on the order, at least one sample for mechanical properties tests shall be taken from one piece out of every group of twenty-six or fraction thereof from the same lot. The samples shall be of full cross-section and of sufficient length to obtain specimens in accordance with 4.5.1.2 (see 6.1j).

4.3.2.2 For tubing and extruded shapes. - Except when a sampling plan has been specified in the contract or on the order, at least one sample for mechanical properties tests shall be taken from each end of each multiple length of tubing or extruded shape. The samples shall be of full cross-section and of sufficient length to obtain specimens in accordance with 4.5.1.2.

4.3.2.3 For Government surveillance tests. - One sample for mechanical properties tests shall be taken from each lot to be tested. Samples shall be of full cross section and of sufficient size to obtain specimens in accordance with 4.5.1.2.1.2.

4.4 Examination.

4.4.1 Visual. - All material shall be subject to visual examination for compliance with workmanship requirements (see 3.9).

4.4.2 Preparation for shipment. - Examination shall be made to determine compliance with the requirements for preparation for shipment (see section 5).

4.5 Tests.

4.5.1 Test specimens.

4.5.1.1 Hydrogen analysis specimens. - Hydrogen analysis specimens shall be taken from a location within the sample corresponding to the finish machined surface. Specimens for this purpose may be taken from mechanical test samples.

4.5.1.2 Tension and impact specimens.

4.5.1.2.1 Location of specimens.

4.5.1.2.1.1 For acceptance testing. - Two tensile and two Charpy impact test specimens shall be taken from each sample, selected in accordance with 4.3.2 from the locations indicated on the applicable drawing, except that when no location is shown on the drawing, specimens from tubes shall be taken from material at least one and one half wall thicknesses from the end, or original end of a multiple length, so that the longitudinal center lines of the specimens at mid length (of the specimens) are tangent to a circle located as close to midwall of the critical section as possible; or in the case of a forging, as close to the middle of the critical section as possible. Charpy specimens shall be notched on the side nearest the bore surface.

4.5.1.2.1.1.1 For tubular components. - Test specimens shall be taken from the 12, 6, 3 and 9 o'clock positions, consecutively, as may be necessary to obtain sufficient tests. Additional specimens, if required, may be taken from a position diametrically opposite the preceding specimen unless a specimen has previously been taken from that location.

4.5.1.2.1.2 For government surveillance testing. - Four tensile and ten Charpy V-notch impact test specimens shall be taken from each sample, selected in accordance with 4.3.2.3 from the locations indicated in 4.5.1.2.1.1. Two of these tensile specimens and five of these Charpy V-notch impact specimens shall be tested by contractor and the remainder shall be tested by a Government testing facility.

4.5.1.2.2 Type of specimens.

4.5.1.2.2.1 Tension test specimens. - Tension test specimens shall be machined to the form and dimensions of the largest obtainable round specimen shown in method 211 of Fed. Test Method Std. No. 151, except that at the option of the contractor an R2 specimen may be used.

4.5.1.2.2.2 Impact test specimens. - Charpy V-notch impact specimens shall be machined to the form and dimensions shown in method 221 of Fed. Test Method Std. No. 151. When a standard-sized impact specimen can not be obtained, the contractor, at the option of the contracting officer, may be required to demonstrate, by special tests prescribed by the contracting officer and agreed to by the contractor, that the material he proposes to furnish is satisfactory insofar as impact resistance is concerned.

4.5.2 Test procedures.

4.5.2.1 Hydrogen analysis. - The hydrogen content shall be determined in accordance with the procedure specified in Specification MIL-T-46038.

4.5.2.2 Tension tests. - Tension tests shall be conducted in accordance with method 211 of Fed. Test Method Std. No. 151. The yield strength shall be determined by the offset method by plotting a stress-strain diagram. The limiting offset shall be 0.10 percent (0.001 inch per inch of gage length). The strain rate shall not exceed 0.005 in./in./min. up to the yield strength at 0.2 percent offset.

4.5.2.2.1 Elevated temperature tensile tests. - Tensile tests at elevated temperature shall be conducted in accordance with ASTM Designation: E21-58T, except that the test temperature and time at temperature shall be as follows:

Test temperature : 500°F
Time at temperature: 30 minutes

4.5.2.2.2 Yield strength. - If the average yield strength for each sample is above the minimum yield strength requirements of the drawing, the piece will be accepted as having met the yield strength requirements.

4.5.2.2.3 Ductility. - The average reduction-in-area and elongation shall be determined for each sample. If each average is equal to, or above the average set out in table I for the upper limit of the required yield strength range, the piece will be accepted as having met the reduction-in-area and elongation requirements.

4.5.2.3 Impact tests. - Charpy V-notch impact tests shall be conducted in accordance with method 221 of Fed. Test Method Std. No. 151. The temperature of the test specimen at the time of fracture shall be -40°F ± 2°F. The error in the Charpy machine shall not exceed ± 1 ft.-lb. for energy values up to 20 ft.-lbs., or ± 5 percent for energy values over 20 ft.-lbs. when the machine is tested using comparison specimens prepared by Watertown Arsenal (see 6.3). This comparison shall have been made within one year prior to the time of inspection testing.

4.5.2.3.1 Impact resistance. - If the average value for each sample is equal to or above the value given in table I opposite the upper limit of the required yield strength range, the piece will be accepted as having met the requirements for impact resistance.

4.5.2.4 Density tests. - Density tests shall be performed in accordance with ASTM Designation: B311-58.

4.6 Rejection and retests or resubmittal. - Rejection and retests or resubmittal of rejected lots shall be in accordance with the general section of Fed. Test Method Std. No. 151.

5. PREPARATION FOR DELIVERY

5.1 Preservation and packaging.

5.1.1 Level C. - Cleaning, drying, preservation and packaging shall be in accordance with the manufacturers commercial practice.

5.2 Packing.

5.2.1 Level C. - Packing shall be in accordance with commercial practice adequate to insure acceptance and safe delivery by the carrier for the mode of transportation employed.

5.3 Marking. - In addition to any special marking required by the contract or order, shipments shall be marked with the lot number, purchase order numbers, and in accordance with the requirements of MIL-STD-129.

6. NOTES

6.1 Ordering data. - Procurement documents should specify the following:

(a) Title, number, and date of this specification.

(b) Applicable drawing numbers.

(c) Quantity and dimensions of components.

(d) Minimum yield strength or yield strength range.

(e) Impact requirements, if other than in table I.

(f) Special identification marking not covered in 3.8.

(g) When other than vertical quenching is permitted (see 3.4).

(h) When special marking for shipment requirements are necessary (see 5.3).

(i) Sampling plans when applicable.

(j) Location of specimens for mechanical properties tests and location of critical section should be shown on applicable drawings.

(k) Sampling for hydrogen content if other than in 4.3.1.

6.2 Definitions.

6.2.1 Critical section. - The critical section is the thickest section of a piece which must meet the mechanical property requirements of table I. The properties shown in table I may not be obtainable in all thicknesses covered by this specification. Proper precautions should be taken, by sufficient investigation or tests, to establish that the materials properties can be attained in the required thickness.

6.2.2 Prolongation. - A prolongation for purposes of inspection and tests is defined as an extension beyond the finished component length, where the diameter and mass distribution of the extension are not less than those of the component at a point coincident with the end of the finished component from which it extends.

6.3 Information regarding comparison tests on Charpy impact machines employing Watertown Arsenal comparison specimens can be obtained from the local Ordnance District or from the Commanding Officer, Watertown Arsenal, Watertown 72, Mass.

6.4 Copies of OO Form 1212, Report of Treatment and Test should be obtained as directed by the Contracting Officer.

Custodians:

Army - Ordnance Corps

Preparing Activity:

Army - Ordnance Corps

SECTION D

Trepanning Machine Shop Practices

Trepanning and Parting of Titanium Cyclinders

TREPANNING MACHINE SHOP PRACTICES

INTRODUCTION

Trepanning or trepan boring is used in such widely separated scientific fields and trades as medical surgery (sometimes referred to as rotary sawing in this field), geology, engineering, woodworking and metal cutting. In most engineering and physical sciences trepanning has been resorted to only when either (1) cores of material are required for examination such as in geology or (2) recovered core material in solid bar form* is of much greater value than machined chips of the same material resulting from the normal drilling and boring methods. While trepanning of concrete bars has become commonplace, the application of trepanning in metal cutting has been limited, not only because of the "special" tooling configuration and high pressures used to remove the chips generated, but also because of the availability of the commonly used drilling and boring methods.

MACHINE TOOL WORK CONSIDERATIONS

Assuming, for the sake of simplicity, that both conventional drilling and boring equipment and trepanning equipment are equally efficient, for all depths of holes the amount of work required to produce a hole is proportional to the volume of material removed. When conventional drilling and boring equipment is used, a 4 inch diameter hole requires that 12.57 cubic inches of material be removed for each inch of depth. Trepanning the same size hole removes only 5.5 cubic inches per inch of depth, the difference in volume being the resulting core. In this case trepanning would require only 44% as much work as drilling and boring. Figure 1 shows the relationship between the volume of material removed by trepanning versus hole diameter based on a 0.5 inch annular groove produced in the trepanning operation. For a one inch diameter hole, of course, 100% of the total volume is removed.

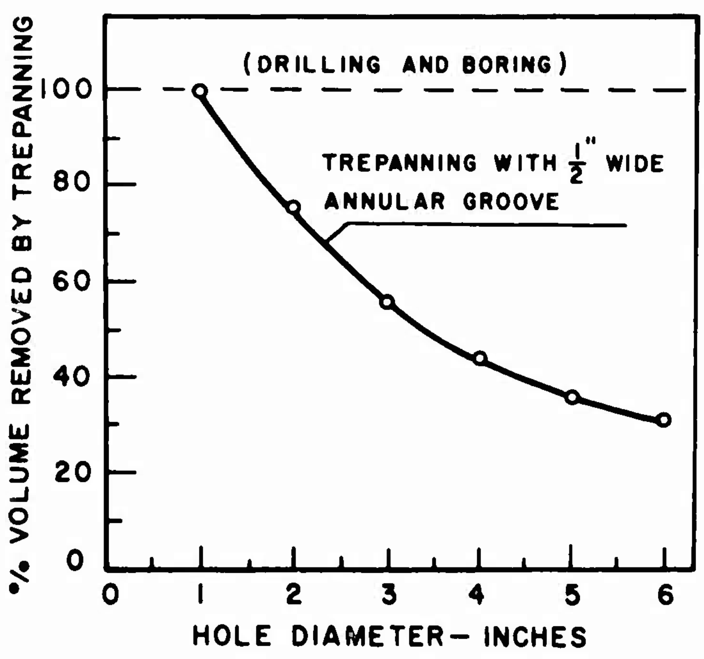


FIGURE 1

CONVENTIONAL DRILLING AND BORING

Conventional drilling and boring of titanium can be done at approximately 30-50 feet per minute with feeds of about .003"-.005" per revolution.

* "Trepanning Titanium Saves Time and Material". S. E. Siemen and N. Rosato. American Machinist. August 30, 1954.

In order to illustrate the machine time required to perform a typical deep hole drilling and boring operation, the following steps, together with their appropriate times, are required to produce a 4.150" diameter hole 18" long:

A.	Drill	- 1/2" drill	-	1 hour, 50 minutes
B.	Drill	- 1" drill	-	1 hour, 40 minutes
C.	Drill	- 2" drill	-	3 hours
D.	Drill	- 3" head	-	3 hours, 30 minutes
E.	Drill	- 4" head	-	4 hours, 10 minutes
F.	Finish bore	- 4.150"	-	1 hour, 20 minutes

This time analysis, including the time required for tool changes, is demonstrated graphically in Figure 2.

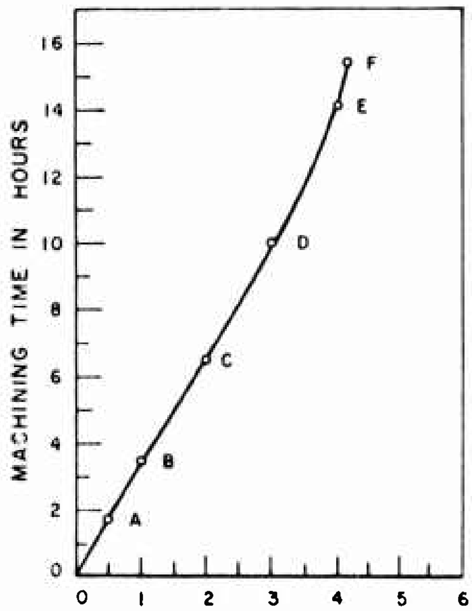


FIGURE 2

TREPANNING

Trepanning of a 4.150" diameter hole can be done at approximately 60 r.p.m. (cutting speed 65 feet per minute) with feeds of .006" per revolution. A general view of the trepanning operation is shown in Figure 3.

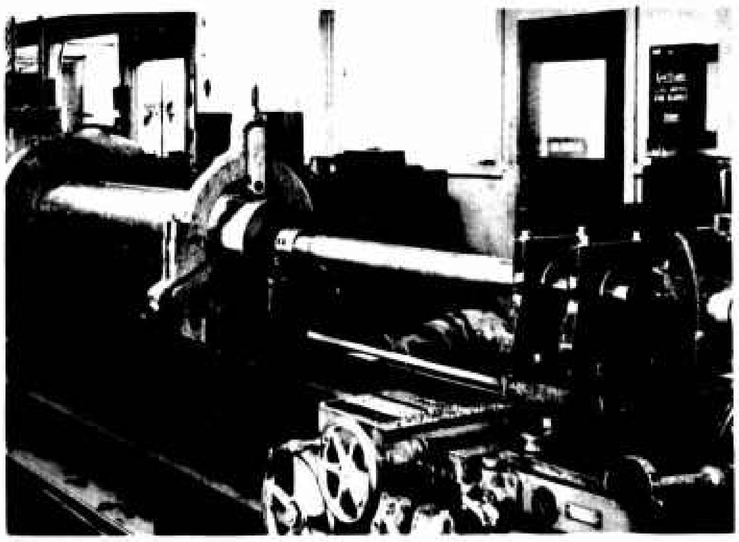


FIGURE 3: TREPANNING SET-UP

In trepanning it is necessary, however, to counterbore an annular groove approximately 1-1/2" deep prior to trepanning to receive the trepan head. An adjustable spotting head, utilizing the three step toolbit which is later described in detail, is used for this counterboring operation as is shown in Figure 4.

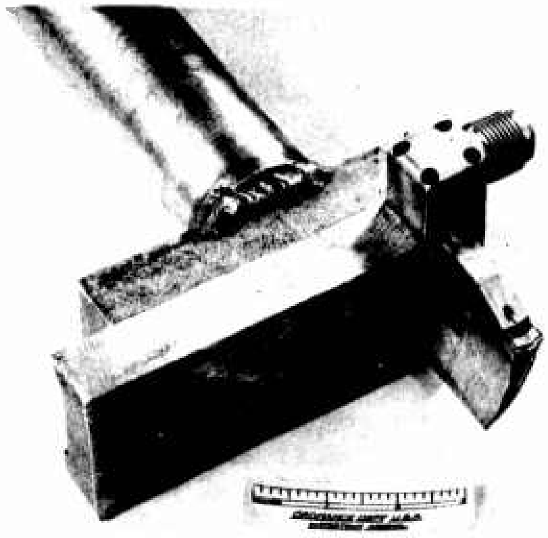


FIGURE 4: CLOSEUP OF ADJUSTABLE SPOTTING HEAD

Counterboring is accomplished at the same speed as trepanning but at half the feed, or .003" per revolution. As an illustration of the time required to trepan a hole Figure 5 shows the time required to counterbore and trepan the same 4.150" diameter hole cited above to a depth of 18 inches. The counterboring operation takes twenty minutes while the trepanning operation takes forty-five minutes -- or a total machine time of one hour and five minutes.

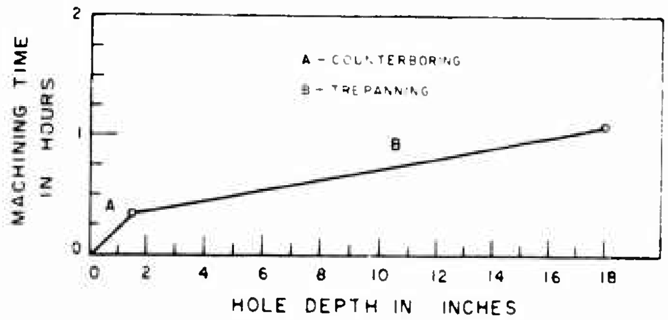
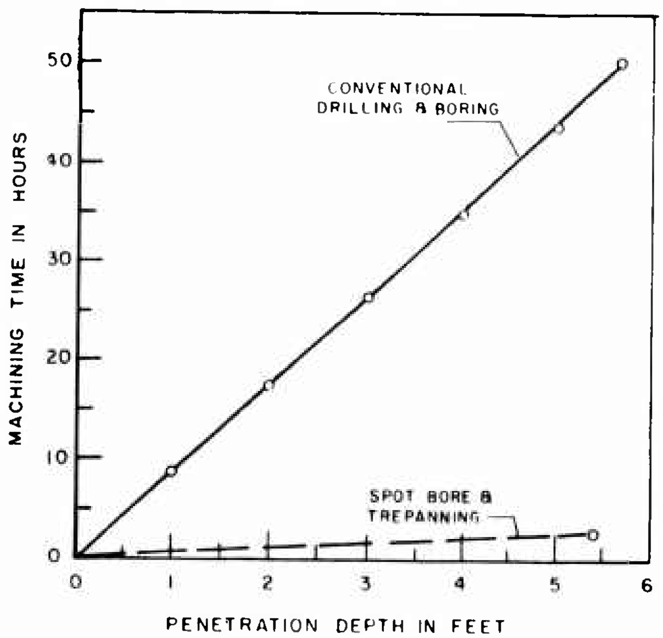


FIGURE 5

COMPARISON OF DRILLING AND BORING VS TREPANNING

From Figure 6 it can be seen that considerable savings in machining time can be realized by the trepanning technique. It is also demonstrated that this time saving becomes markedly greater as the penetration depth increases. In addition to this increased efficiency of trepanning, it must be remembered that far more accurate holes are machined by this method with essentially no runout over long lengths. This lack of runout eliminates the necessity of re-machining outside surfaces to maintain concentricity.



DRILLING TIME VERSUS TREPANNING TIME FOR TITANIUM ALLOY 4 150" DIA BY 68" LONG

FIGURE 6

TREPAN DESIGN

1. Head, Tube, and Stem.

A typical head for trepanning of titanium, as shown in Figure 7, is rough machined from a short solid bar of alloy steel. In the rough machining operation the head is machined to within one-sixteenth of an inch of the finished size on all dimensions. The chip groove, and the counterbore that will receive the shank upon assembly, are also roughed out at this time. The roughed head is heat treated to a hardness of Rc 37-42, and is then finish-machined to the dimensions shown on drawing MSB 441. (All drawings referenced in this report are appended).

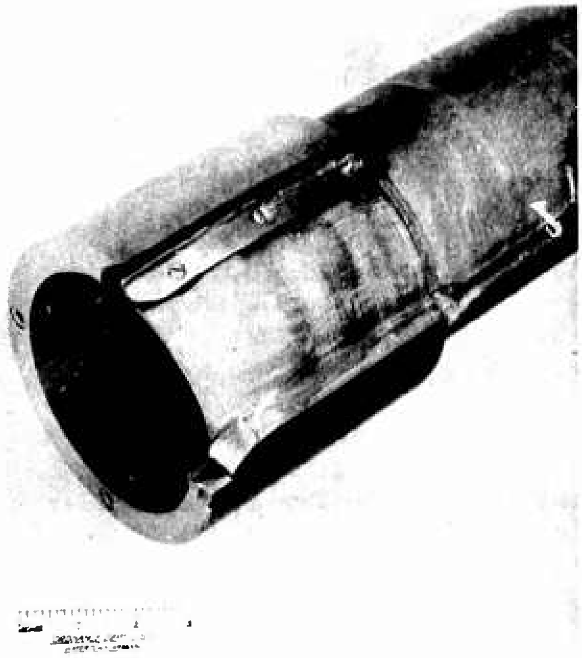


FIGURE 7: CLOSEUP OF TREPAN HEAD

The tube of the trepan is made of commercially available seamless tubing. The optimum cross sectional thickness of the tube for a typical trepan head is .090". The inner diameter of the tube is selected to provide ample clearance for the titanium core to pass thru freely while the trepan is advanced into the rotating work piece. The outer diameter of the tube is relieved to provide a passage way for the removal of chips generated by the tool tip.

A stem of mild steel is machined as shown on drawing MSB 442 with a shouldered flange on one end. The flanged portion of the stem is fitted into one end of the tube then welded in place. The stem is left oversize until after assembly of the tube to the trepan head.

2. Rollers and Pins.

In early experiments on the trepanning of titanium, it was demonstrated that conventional trepans of the German design, which had been employed in the trepanning of steel, were not suited to the trepanning of titanium because of the severe seizing and galling characteristics of this material. The carbide wear pads used on conventional trepans, when applied to titanium, had the tendency to fuse and gall even with oil pressures of 2000 p.s.i.. Substitution of bunting bronze in lieu of the carbide wear pads proved futile, as the rapid erosion of the bronze wear pads changed the diameter of the head drastically, thereby wedging the head in the titanium and producing a tapered hole in a short depth of penetration.

It was apparent that a guidance system must be designed to overcome the galling and seizing problem while maintaining true axial alignment of the trepan. To solve this problem double openings were cut through the wall of the trepan head at two points. The head was cross drilled axially through the openings to support hardened tool steel pins, which would accommodate hardened tool steel rollers and thrust washers. The pin holes were so positioned as to permit the surface of the rolls to provide a radial clearance of .010" over the surface of the head.

The roller guidance system uses the chip tool pressure to force the rolls against the bore surface and maintain axial alignment of the trepan. (Detailed information is shown in drawing MSB 441).

3. Oil Pressure System.

The oil pressure system provides constant oil pressure at the cutting area regardless of the depth of penetration of the trepan, and eliminates the need for intricate and expensive packing gland or stuffing box systems. It provides a constant stream of oil or coolant under extremely high pressure which is directed upon the cutting tool. This coolant serves a threefold purpose:

a. It provides for a film of oil or coolant between the cutting tool and work reducing the friction between the forming chip and tool and preventing metal to metal contact between the tool and the workpiece.

b. It provides a means of lubricating the roller bearings with oil or coolant under pressure in the trepan head to solve the problem of galling.

c. It provides for the evacuation of the machined chips within the limits of the clearance formed between the outside of the trepan tube and the circumference of the bore machined in the work piece.

Details of the high pressure oil tube and fittings are shown in drawing MSB 441, MSB 442 and MSB 443.

The system is designed to operate at 1000 psi at approximately 12 gpm. The coolant presently used is "Cimcool S-2 Concentrate" in a 20:1 mixture with water. The pump used for the system is a 40 HP variable volume, variable pressure, positive displacement type, capable of delivering up to 5000 psi pressure at 20 gpm.

TOOL BIT DESIGN

The three-step composite tool bit consists of a Moly-Tungsten type tool steel, rough machined, heat treated to a hardness RC 60-62, and finish machined to the dimensions shown on drawing MSO-300. A tungsten carbide tool tip is silver brazed to the tool steel block and ground with a three-step design at the forward portion of the tool bit. Tungsten carbide of a grade 883 has been found to be the most successful type for machining titanium. The same tool bit is used interchangeably amongst the trepan head, counterboring tool, and the parting tool.

The composite tool carries a shank 1/4" diameter x 1" long. The tool bit is tightly fitted into a slotted receptacle machined into the face of the trepan head. It is held in place by two set screws against a flattened portion of the shank. The tool bit is positioned in the face of the trepan head so that the outer edge of the tool is offset .015" over the radial surface of the head, and also protrudes approximately .015" from the inside circumference of the head. The protrusion of the tool in the inside of the head provides the necessary clearance to allow the core to pass into the tube of the trepan, but will not allow chips to accumulate between the core and the head.

A chip breaker designed to generate the proper type chip is of extreme importance as the chips generated must be over-broken and small enough to pass with the coolant through the chip groove area of the trepan head freely in any disoriented fashion for further evacuation between the trepan tube and the bore of the workpiece to the bed of the lathe.

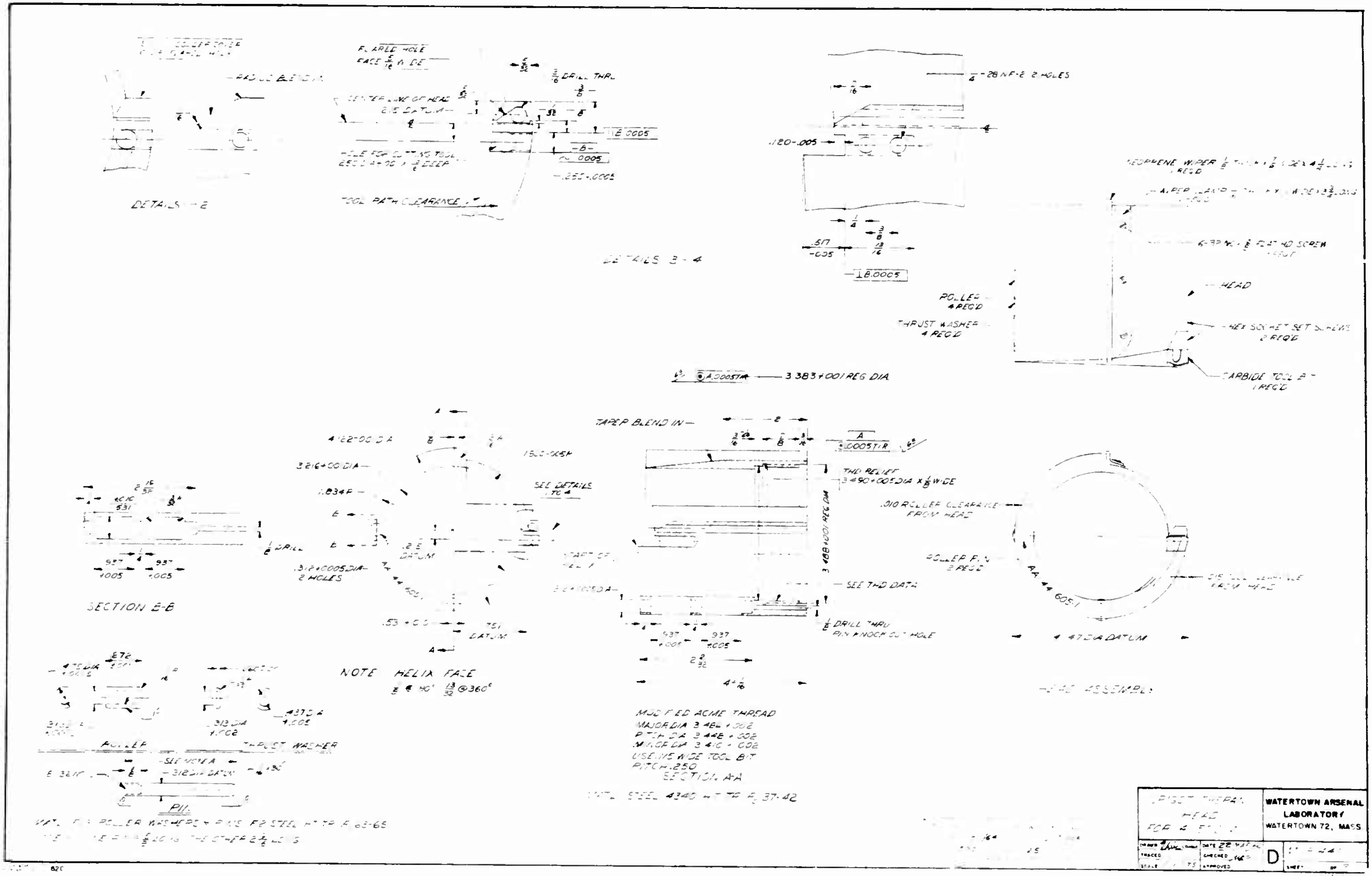
The four items referred to above, when assembled, comprise a trepan tool engineered to successfully produce economical, high diameter-to-depth ratio bores in titanium metals. (Patents* on this tool have been issued to the inventors and assignment made to the Government).

* Patent #2,863,341
Issued 9 December 1958.

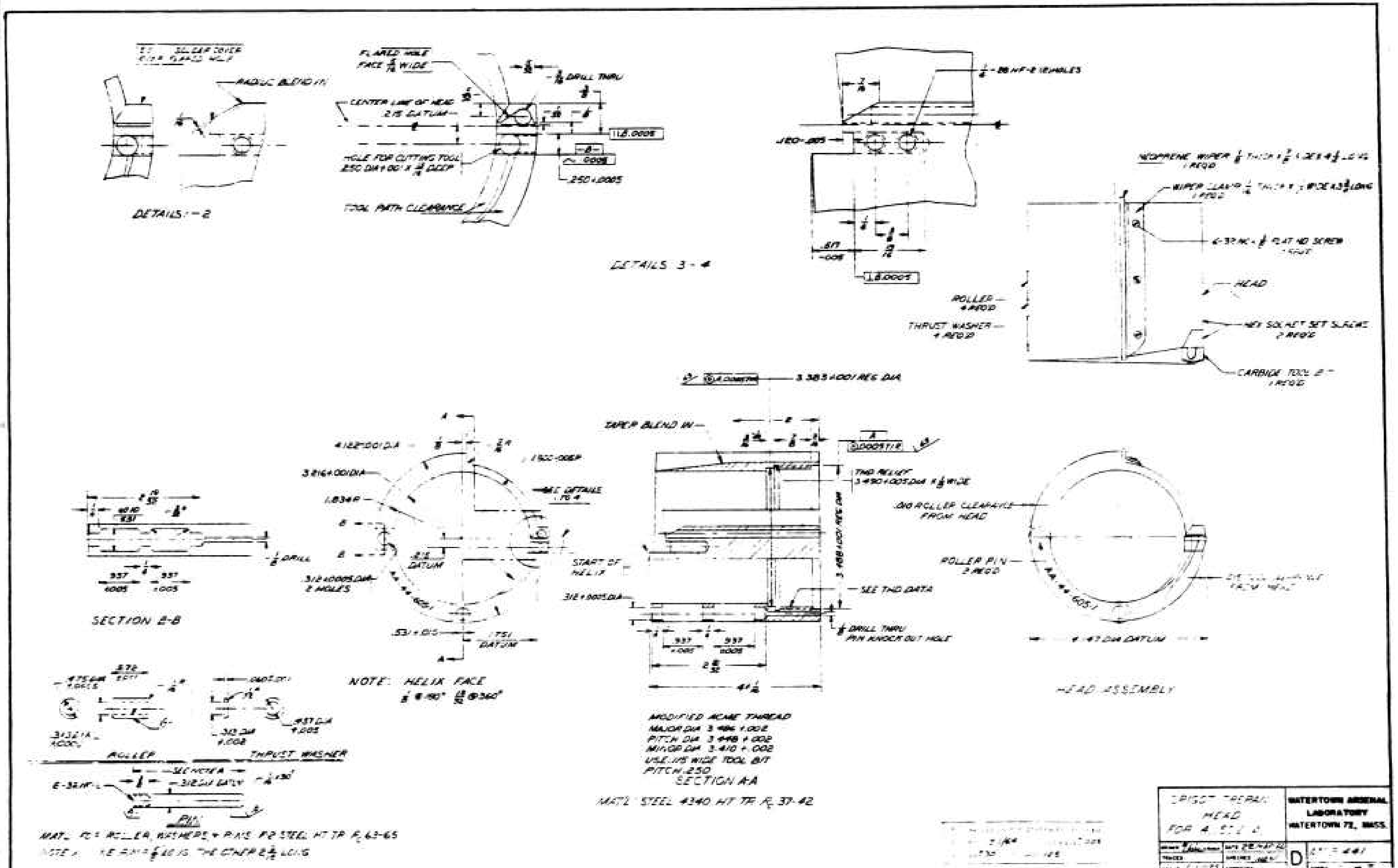
S. E. Siemen
N. Rosato

WATERTOWN ARSENAL LABORATORIES
WATERTOWN, MASSACHUSETTS

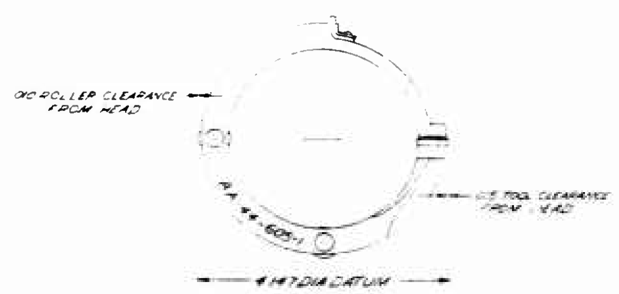
12 April 1960



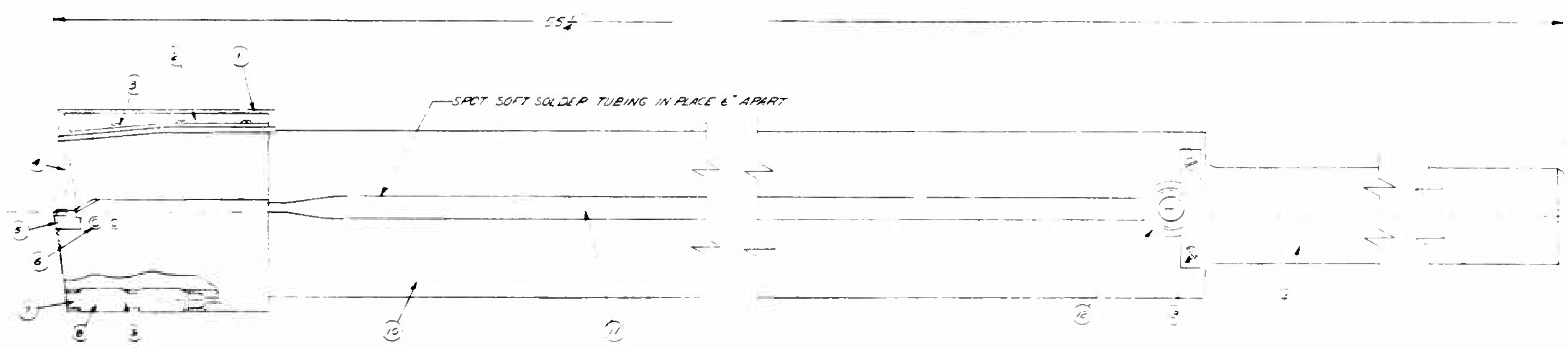
DETAILS 3 - 4
SECTION B-B
NOTE HELIX FACE
SECTION A-A
MODIFIED ACME THREAD
PITCH .250
ROLLER
THRUST WASHER
4 REQ'D
HEAD
CARBIDE TOOL BIT
1 REQ'D
HEX SOCKET SET SCREWS
2 REQ'D
3.383+.001 REQ DIA
TAPER BLEND IN
SEE THD DATA
TOOL PATH CLEARANCE
.010 ROLLER CLEARANCE
FROM HEAD
4.47 DIA DATUM
WATERTOWN ARSENAL
LABORATORY
WATERTOWN 72, MASS
D



DETAILS 1-2
RADIUS BLEND IN
FLARED HOLE FACE 3/16 WIDE
CENTER LINE OF HEAD 2.15 DATUM
HOLE FOR CUTTING TOOL .250 DIA +.001 x 3/16 DEEP
TOOL PATH CLEARANCE
1/8 DRILL THRU
.250 +.0005
DETAILS 3 - 4
1/4 - 28 NF-2 (6) HOLES
NEOPRENE WIPER
WIPER CLAMP
6-32 NC x 1/8 FLAT HD SCREW
HEAD
ROLLER 4 REQ'D
THRUST WASHER 4 REQ'D
HEX SOCKET SET SCREWS 2 REQ'D
CARBIDE TOOL BIT 1 REQ'D
3.383 +.001 REG DIA
TAPER BLEND IN
THD RELIEF 3.490 +.005 DIA x 3/16 WIDE
.010 ROLLER CLEARANCE FROM HEAD
ROLLER PIN 2 REQ'D
SEE THD DATA
1/8 DRILL THRU PIN KNOCK OUT HOLE
4.47 DIA DATUM
HEAD ASSEMBLY
4.122 +.001 DIA
3.816 +.001 DIA
1.834 R
.312 +.0005 DIA 2 HOLES
.531 +.015
.751 DATUM
.812 DATUM
.1900 DEEP
SEE DETAILS 1 TO 4
START OF HELIX
.312 +.0005 DIA
NOTE: HELIX FACE 1/8 @ 180° 13/32 @ 360°
SECTION B-B
1/8 DRILL
ROLLER
THRUST WASHER
PIN
MODIFIED ACME THREAD
MAJOR DIA 3.486 +.002
PITCH DIA 3.448 +.002
MINOR DIA 3.410 +.002
USE .115 WIDE TOOL BIT
PITCH .250
SECTION A-A
MAT'L STEEL 4340 HT TR R_c 37-42
MAT'L FOR ROLLER, WASHERS + PINS FB STEEL HT TR R_c 63-65
SPIGOT TREPAN HEAD
WATERTOWN ARSENAL LABORATORY WATERTOWN 72, MASS.
D



PART NO	NAME	MATERIAL	NO REQ'D	DWG NO
	WIPER	NEOPRENE	1	MSB 441
2	WIPER CLAMP	STEEL	1	MSB 44
3	6-32 NC x $\frac{3}{8}$ FLAT HEAD	STEEL	3	
4	TREPANNING HEAD	STEEL	1	MSB 441
5	TOOL BIT	CARBIDE	1	MSC 300
6	$\frac{1}{4}$ 28NF x $\frac{3}{16}$ HEX SOCKET SET SCREW	STEEL	2	
7	ROLLER PIN	F-2 STEEL	2	MSB 44
8	ROLLER	F-2 STEEL	2	MSB 441
9	THRUST WASHER	F-2 STEEL	2	MSB 44
10	TREPANNING TUBE	1020 STEEL	1	MSB 442
11	HIGH PRESSURE TUBE	STEEL	1	MSB 442
12	HIGH PRESSURE FITTING	4140 STEEL	1	MSB 442
13	10-24 NC x $\frac{3}{8}$ ROUND HEAD HEAD	STEEL	2	
14	STEM	4140 STEEL	1	MSB 442

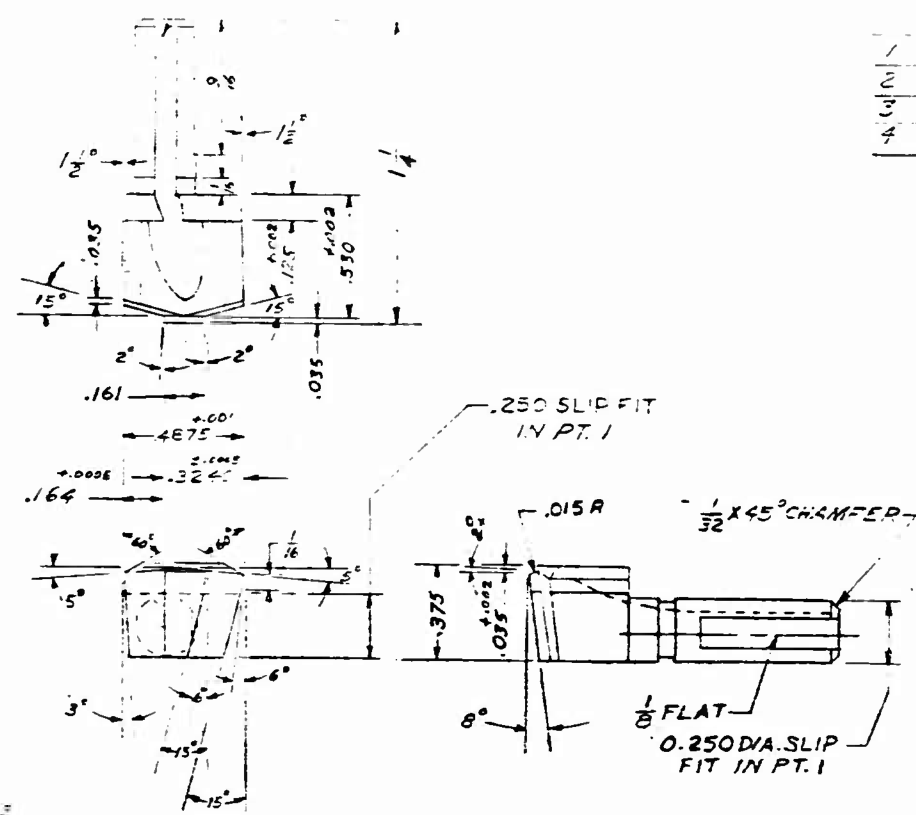


NOTE: AXIAL ALIGNMENT OF ASSEMBLY 0.002 TIR

SPIGOT TREPAN ASSEMBLY FOR 4.150 DIA	WATERTOWN ARSENAL LABORATORY WATERTOWN 72, MASS
DATE 29 MAR 60 SCALE 1/1	D MSB 443

NOTE: THIS TOOL BIT USED ON TREPAN HEAD LISTED BELOW

1	2.410 DIA
2	4.150 DIA
3	4.300 DIA
4	4.500 DIA



TOLERANCE ON DIMENSIONS NOT OTHERWISE SPECIFIED
DECIMAL ± .005
FRACTIONAL ± 1/64
ANGULAR ± 0°-5'

TREPAN TOOL BIT
CARBIDE TIPPED 883—K6 OR EQUAL

CARBIDE TOOL BIT FOR TREPANING TITANIUM		WATERTOWN ARSENAL LABORATORIES WATERTOWN 72 MASS	
DRAWN:	DATE 7 MAY 59	B	MSC. 300
TRACED: VALAVANIS	CHECKED:		
SCALE: 2/1	APPROVED:		SHEET 4 OF 4

PARTING OF TITANIUM CYLINDERS

In conjunction with development work at Watertown Arsenal Laboratories on the trepanning of titanium and its alloys, considerable thought and effort was devoted to the problems of sectioning large cylindrical billets, both trepanned and solid. Cutting off by means of a saw was inefficient and uneconomical and necessitated the additional operation of facing off in a lathe after completion of the sawing. One solution to this problem was to section the billet in a lathe using a parting tool. This method, using conventional techniques, was found suitable for diameters up to two inches. However, the tool tended to wander and break on larger sizes.

The ultimate solution again made use of the three step carbide tipped tool bit. It was inserted in a heavy duty steel tool holder approximately 10 inches long, 7/16 inch wide, and 3 inches deep. A coolant pipe was affixed as shown in Figure 1. The tool holder was fastened in a tool block mounted on the cross slide of a lathe. The coolant used in these parting operations was "Simcool S-2 Concentrate" with a water to concentrate ratio of 25 to 1. The use of a high pressure system provides assurance of constant coolant flow to the cutting tip throughout the operation. A feed of 0.003 i.p.s. and a turning speed of 32 r.p.m. was found to produce optimum results.

FIGURE 1: PARTING TOOL HOLDER W/TREPAN TOOL TIP AND OIL PRESSURE TUBE.

When parting sections of long cylinders after the core has been removed by trepanning, a special mandrel, shown in Figure 2, was inserted in the bore of the cylinder to provide rigid support during the parting operation and prevent breakage of the parting tool.

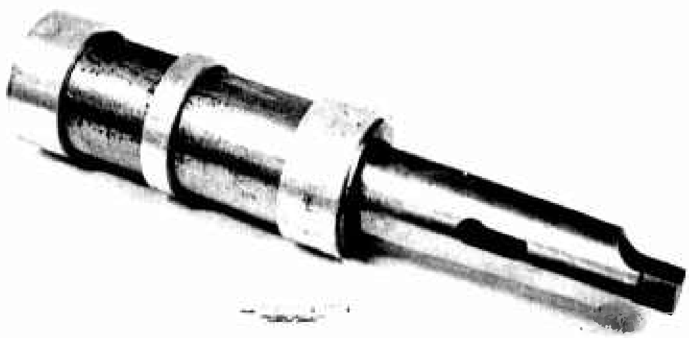


FIGURE 2: SPECIAL MANDREL.

PARTING OF TITANIUM CYLINDERS (CONT)

The support mandrel and a typical setup of the parting of a trepanned titanium cylinder are shown in Figure 3.

For purposes of comparison the case of sawing vs parting can be cited for a 14 inch diameter solid titanium cylinder. The saw cutting operation took more than 3 hours as opposed to 40 minutes for parting. This was another example of the value and versatility of the carbide tipped trepanning tool bit.

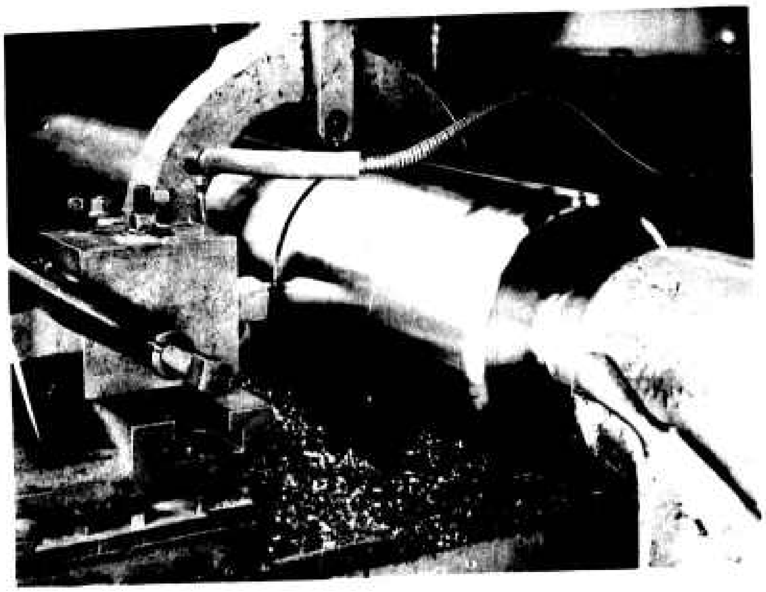


FIGURE 3: PARTING OF TREPANNED CYLINDER.

S. E. Siemen
N. Rosato

Watertown Arsenal
11 April 1960

SECTION E

NEW HIGH-STRENGTH TITANIUM ALLOY

NEW HIGH-STRENGTH TITANIUM ALLOY

INTRODUCTION

The Ordnance Corps of the U. S. Army has been actively searching for materials which will reduce the weight of military equipment. A new titanium alloy has been developed which, on a strength-weight basis, is equivalent to steel at a yield strength of 325,000 psi. In some special weapons, the weight limitations are so stringent that only new high-strength titanium alloys, such as this, provide the high strength-to-weight ratio and toughness which are required. This new alloy has evolved from the materials research program of Watertown Arsenal Laboratories, a program aimed at developing improved materials for Ordnance application.

TYPES OF TITANIUM ALLOYS

Titanium alloys are generally separated into three basic types designated (1) alpha, (2) beta, and (3) alpha + beta. These designations refer to the metallurgical phases which determine alloy behavior. The alpha alloys (which include unalloyed titanium) possess a stable single phase structure which is not amenable to strengthening by heat treatment. Therefore, only moderate strengths can be developed in this type of alloy by solid solution and/or cold work.

The meta-stable beta type alloy can be likened to stainless steels in that it is relatively soft in the annealed (solution-treated condition). In this condition it is ductile and can be readily formed or worked at ambient temperatures. It can be strengthened to high levels by cold working and/or aging the meta-stable beta structure. Considerable research is currently in progress under the Department of Defense Titanium Alloy Sheet Rolling Program to develop the beta alloys to full production status.

The alpha-beta type alloys combine both phases and may be used in the annealed condition, if moderate strength and good ductility are required, or after solution treatment and aging to produce higher strengths and somewhat less, but adequate, ductility. High-strength, alpha-beta titanium alloys are currently being forged, rolled, and extruded into components for a number of Ordnance Corps applications.

COMMERCIAL ALPHA-BETA TITANIUM ALLOYS

There are currently commercially available a variety of proven alpha-beta type titanium alloys. Typical mechanical properties obtainable on some of the more widely used alloys are given in Table I. On a strength-weight basis steels with yield strengths ranging from 230,000 psi to 300,000 psi would be required to compete with the titanium alloys in Table 1.

TABLE I

TYPICAL PROPERTIES REALIZED BY WATERTOWN ARSENAL IN FABRICATION OF COMMERCIAL ALPHA-BETA TITANIUM ALLOYS.

ALLOY TYPE NOMINAL COMPOSITION	T.S. (Psi)	Y.S. (Psi)	EL. (%)	R.A. (%)	IMPACT AT -40°F (FT-LBS)
6AL-4V	150,000	130,000	15	40	14
7AL-4V	170,000	150,000	12	35	10
5AL-1.5Fe-1.4Cr-1.2Mo	185,000	170,000	10	25	7

YIELD STRENGTH AT 0.1% OFFSET

Ti-6Al-6V-2Sn-½Fe-¼Cu ALLOY

To fulfill the need of better materials for critical Ordnance components, a new alloy of the above composition has been developed. This alloy is of the alpha-beta type. It can be heat treated to very high strength levels, yet still maintain good ductility and toughness. Typical properties obtained are shown in Figure 1. It should be noted that yield-strength values are in excess of 180,000 psi.

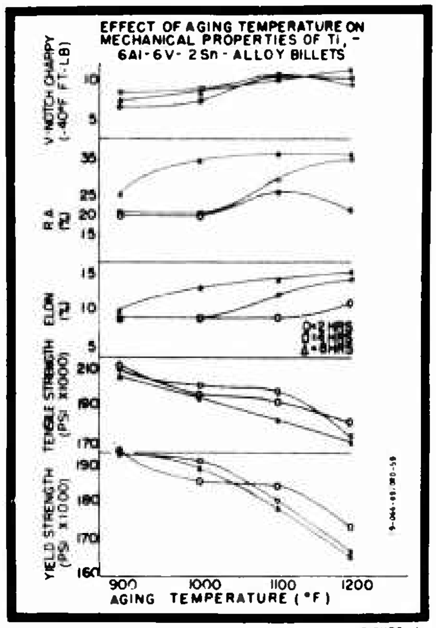


FIGURE 1

Currently, three of the major titanium producers are processing this alloy. Up to the present time, some 20,000 lbs. have been procured by Watertown Arsenal. Most of the material has been utilized in the manufacture of experimental and prototype components for advanced Ordnance weapons. Table II shows mechanical properties obtained from typical prototype items, from certain extruded parts and experimentally "floturned" samples.

This series of high-strength alpha-beta type titanium alloys has been formulated[1] jointly by metallurgists at New York University and Watertown Arsenal Laboratories. These alloys contain about 6%Al-6%V-2%Sn with small quantities of copper, iron, zirconium, and chromium.

MACHINING

The question of machinability often arises when it is proposed to manufacture components from titanium alloys. However, actual "difficulties" are rare. Carbide tools are very effective in machining titanium and slight modifications in tool angle and lubrication are advisable in order to obtain machined surfaces of optimum quality. Equally important are rigid setups

TABLE II

TYPICAL MECHANICAL PROPERTIES OF COMPONENTS FABRICATED FROM DEVELOPMENTAL ALLOY Ti-6AL-6V-2Sn-½Fe-¼Cu ALLOY

TYPE FABRICATION	TEMP. OF FAB. INITIAL (°F)	TEMP. OF FAB. FINAL (°F)	YIELD STRENGTH (Psi x1000)	TENSILE STRENGTH (Psi x 1000)	ELON (%)	R.A. (%)	CHARPY IMPACT (-40°F) (FT-LBS)	SECTION SIZE (IN.)	MAX. SECT. SIZE ROUGH (IN.)	PROCESS (LBS)
OPEN DIE*	1750	1600	181.2$^{(1)}$	189.9	9.5	25.8	6.4	3/4"	2-1/2"	40
CLOSED DIE*	1680	1630	172.5$^{(1)}$	181.0	10.0	27.8	9.3	1"	1-1/2"	10
BACKWARD EXT.	1750	1700	165.0$^{(2)}$	175.0	11.1	26.5	9.6	3/4"	1-1/2"	25
"FLOTURNED" (EXPERIMENTAL)	68	100	162.2$^{(3)}$	169.3	12.0	32.5	(NOTE 1)	.073"	.073"	1

* DATA TAKEN FROM ACTUAL PRODUCTION COMPONENTS.
NOTE 1 - NO TEST CONDUCTED DUE TO THIN SECTION SIZE

HEAT TREATMENT: (1) 1630°F - 1-1/2 HRS - WQ PLUS 1100°F - 4 HRS - AC
(2) 1680°F - 1-1/2 HRS - WQ PLUS 1200°F - 4 HRS - AC
(3) 1100°F - 4 HRS - AC

[1] *Patent being applied for.*

with positive feeds. Cutting rates equivalent to those used in steels of comparable hardness are realized, but with faster feeds and slower speeds. Even "tapping" and "trepanning"[2] of titanium is easy, if simple changes of machining procedures and tool design are made. For example, in Figure 2 the standard tap "A" will seize and break if used in titanium; the standard spiral tap "B" can be used with titanium, but requires "care"; the 52° helix tap "C" is free cutting and is recommended for tapping titanium.

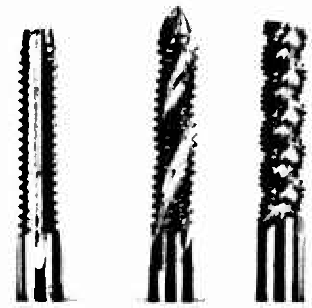
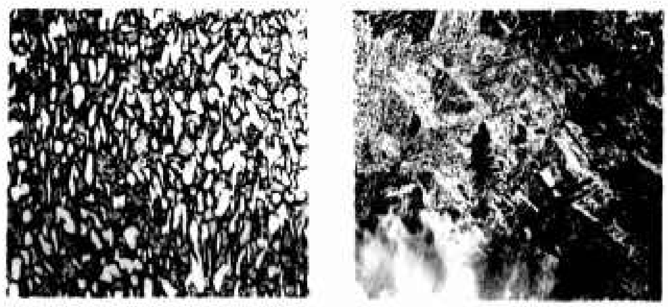


FIGURE 2

FORGING

Forging of titanium not infrequently evokes some skepticism. The marked difference between steel and titanium is that in steel processing grain refinement can be accomplished both by hot working and by heat treatment, whereas in titanium alloys grain refinement can only be obtained by deformation low in the hot forming range. Temperature control has to be maintained within about 25°F. Figure 3 shows the importance of close temperature control. If the alpha-beta transus temperature is exceeded, a coarse brittle structure will result as illustrated by the photomicrograph on the right of Figure 3. To obtain the fine grain structure shown on the photomicrograph in the left of Figure 3, forging must be conducted approximately 50°F below the transus temperature (1720°F) to accomplish a reduction in the order of 50%. At this temperature titanium parts require three to four times greater forging capacity than would be necessary for steel parts of the same size.

EFFECT OF FORGING TEMPERATURE ON TITANIUM MICROSTRUCTURE



FORGED BELOW β TRANSUS X1000 — TOUGH

FORGED ABOVE β TRANSUS X1000 — BRITTLE

Wtn. 639-16,003

FIGURE 3

[2] "Trepanning Titanium" by S. E. Siemen and N. Rosato, Watertown Arsenal Laboratories, AMERICAN MACHINIST, August 30, 1954.

Figure 4 illustrates the effect of forging reduction on resultant mechanical properties.

Since titanium is forged at a substantially lower temperature than steel, forging dies have to be pre-heated to temperatures in the order of 500°F - 600°F to prevent chilling of the titanium parts being forged. A slurry of graphite in silicone oil has been found to be a most effective lubricant.

To minimize seizure between the titanium forging and the dies, draft angles twice those for comparable steel forging dies are necessary.

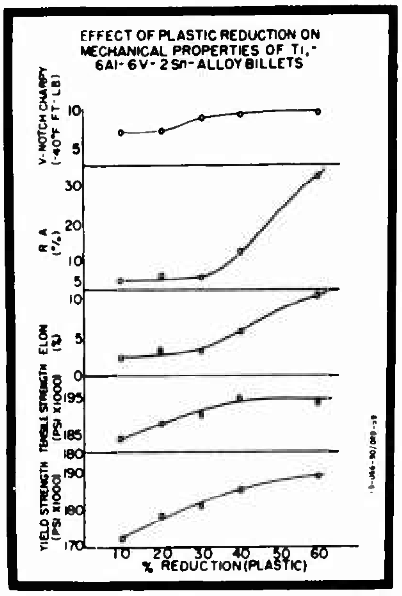
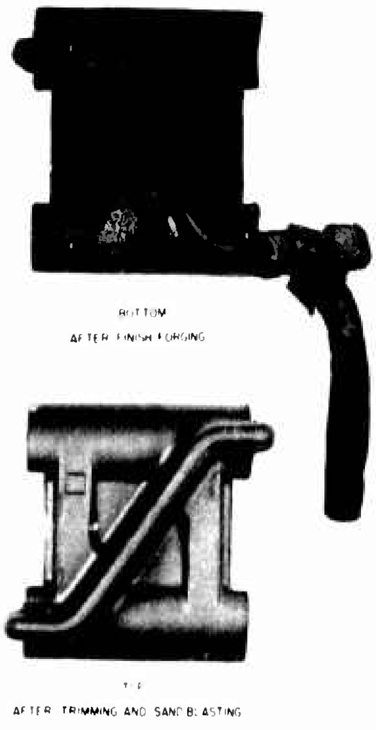


FIGURE 4

Figure 5 illustrates a complex configuration forged in a closed die. It was possible to forge this intricate shape by conducting four separate operations. The first two blocking operations were performed above the beta transus temperature to obtain rough contour each at a reduction ratio of 50%. The last two operations were performed below the beta transus temperature to refine the grain and insure good mechanical properties.



EXPERIMENTAL TANK TRACK GROUSER FORGING OF Ti-7AL-4V ALLOY FORGED ON 10,000 LB HAMMER

FIGURE 5

WELDING

Of course, whenever a new high-strength material is developed the question of weldability always arises. For the new alloy in question, preliminary evaluations have indicated that 150,000 psi yield strength and 5% elongation may be realized in stress relieved weld bends, a significant advance in this important area.

ANTI-GALLING COATINGS

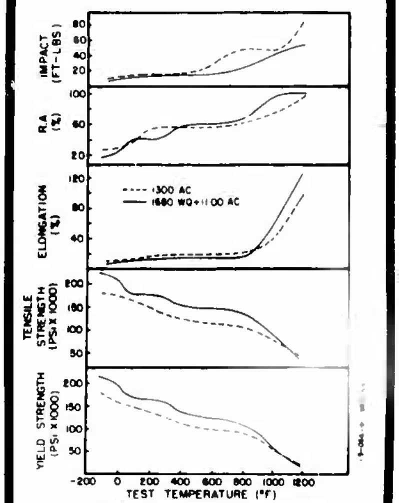
A major disadvantage of titanium alloys is the seizing and galling which occurs between mating parts. A coating consisting of a suspension of colloidal graphite in a phenolic-epoxy resin eliminates galling when applied to the surface of titanium. The coating is applied either by spraying or brushing to a thickness of 1/2 mil and requires a 30-minute cure at 350°F. In threaded connections coating of only the "male" thread is required.

EROSION RESISTANT COATINGS

Titanium alloys are susceptible to erosion when high-velocity hot gases are brought into intimate contact with the material. Flame sprayed coatings of aluminum-oxide, zirconium-oxide, and stainless steel have been found to practically eliminate erosion in certain applications involving single (non-recurring) exposure.

HIGH TEMPERATURE PROPERTIES

Figure 6 shows the strength of this new alloy at elevated temperatures. Briefly, it is much better than the average titanium alloy, and under some conditions it is exceptional. Yield strength values in excess of 100,000 psi can be obtained at temperatures up to 800°F, and at 1000°F tensile strength values up to 100,000 psi can be obtained.



LONGITUDINAL MECHANICAL PROPERTIES OF Ti-6Al-6V-2Sn ALLOY

FIGURE 6

LABORATORY STAGE ALLOYS

In the continuing alloy-development program slight modifications in chemical composition have already produced new alloys with mechanical properties superior to the original. In laboratory size heats some titanium alloys with yield strengths up to 210,000 psi and good toughness have been realized.

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