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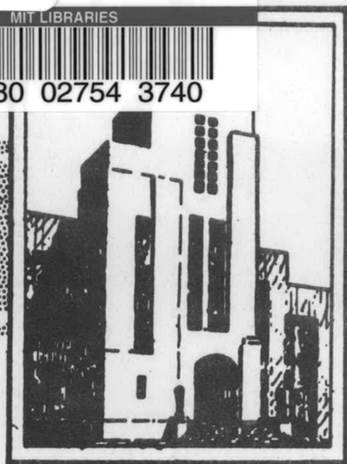

DEPARTMENT OF THE NAVY
DAVID TAYLOR MODEL BASIN

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HYDROMECHANICS

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AERODYNAMICS

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o

APPLIED MATHEMATICS

PROGRESS REPORT

METALLURGICAL INVESTIGATION OF TITANIUM ALLOYS FOR APPLICATION TO DEEP-DIVING SUBMARINES

1 July 1959 through 1 October 1960

by

A.R. Willner and V.E. Sullivan, LTJG, USN

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STRUCTURAL MECHANICS LABORATORY

RESEARCH AND DEVELOPMENT REPORT

December 1960

Report 1482

PRNC-TMB-648 (Rev. 3-58)

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ABSTRACT

To determine the practicability of titanium alloys for use as a submarine hull material, the mechanical properties and notch-sensitivity of five high-strength titanium alloys and a commercially pure titanium were evaluated.

Of the high-strength titanium alloys the MQ or MSM-821 alloy exhibited the least sensitivity to rate of loading, and the greatest resistance to fractures as determined by Charpy V-notch, drop-weight, and explosion crack-starter tests.

A tentative criterion for determining the nil-ductility transition temperature by the Charpy V-notch test has been established.

INTRODUCTION

Preliminary design studies by the David Taylor Model Basin[1] indicated that, on a strength-weight basis, titanium alloys of 120,000-psi yield strength can be used advantageously for the hulls of deep-diving submarines. Supplementing the advantages of the physical and mechanical properties of high-strength titanium alloys are their resistance to sea-water corrosion and their nonmagnetic characteristics. Hence, a program was established[2] to develop and evaluate titanium alloys for application to deep-diving submarines.

Four major producers of titanium alloys were requested to participate in this program[3] through the Department of Defense Titanium Alloy Sheet Program. Each producer was to submit one or more alloys which were believed to have the strength, toughness, and weldability required for submarine service.

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[1] References are listed on page 45.

The experimental program planned to evaluate titanium as a submarine hull material is outlined in Figure 1. The preliminary survey is designed to evaluate the mechanical properties of the alloys and to eliminate brittle alloys. The notch-toughness, fabricability, weldability, and other properties of the acceptable titanium alloys will then be investigated to determine the practicability of titanium for submarine construction.

This report presents the mechanical properties and fracture-transition characteristics of the unwelded titanium alloys which have been submitted. Although some of the tests are still underway, the report has been prepared to make available the significant results found thus far.

MATERIALS AND SPECIMENS

Ten groups of titanium plates were received from the four participating producers between 1 March 1960 and 1 September 1960. All groups except one consisted of four 1-in. by 20-in. by 20 in.-plates; three plates from each group were designated for explosion crack-starter tests and the other for drop-weight and mechanical property tests. For the case of the one group where only one plate was submitted, it was used for the explosion crack-starter test. Table 1 summarizes the chemical analysis of each group and heat received.

The Model Basin designations for each of the submitted alloys are as follows:

The first letter designates the producer:

- C - Crucible Steel
- M - Reactive Metals (formerly Mallory-Sharon)
- R - Republic Steel
- T - Titanium Metals Corporation

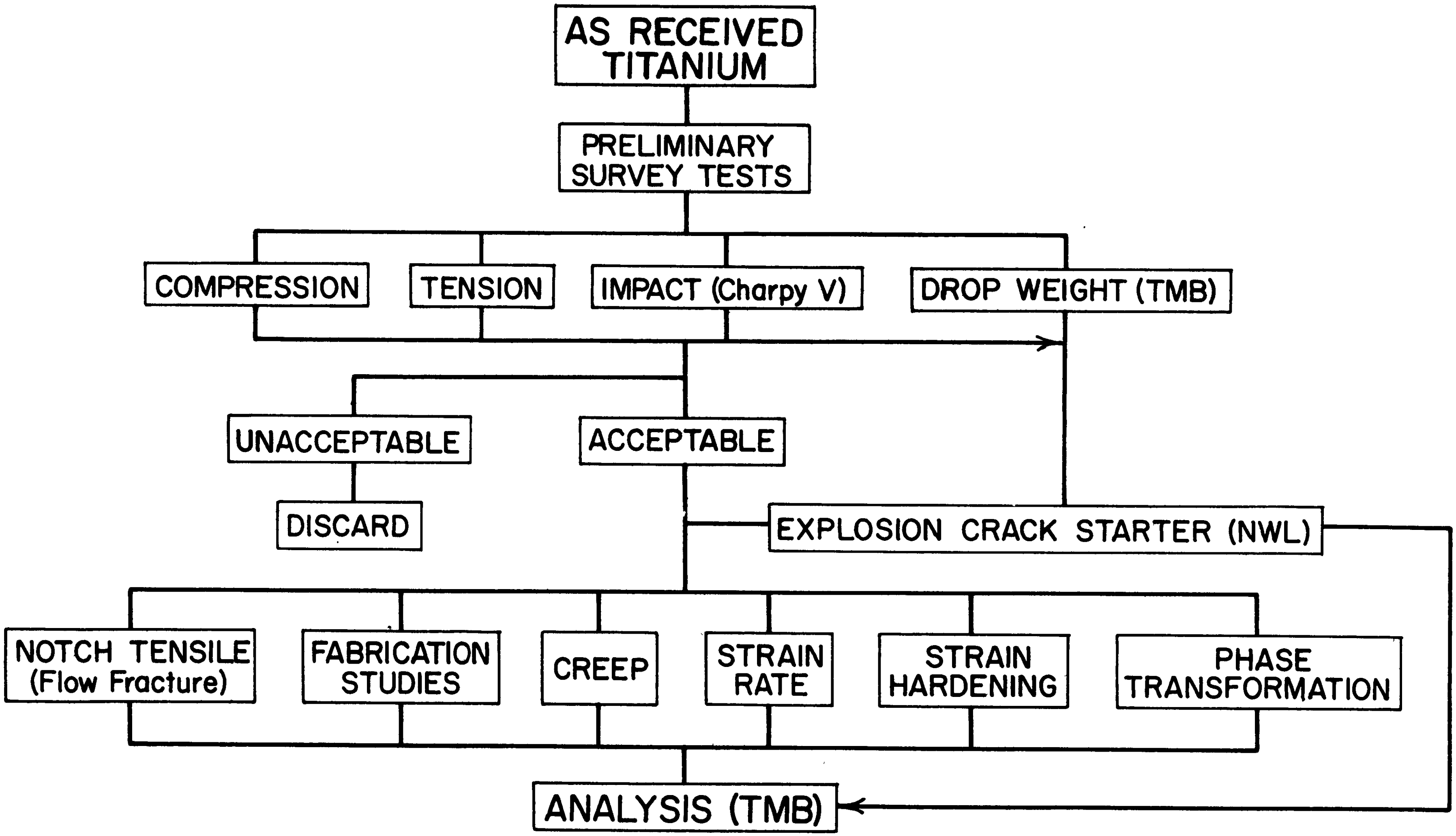

Figure 1 - Planned Experimental Program

TABLE 1

Producers' Chemical Analysis of Titanium Alloy Plates

Alloy Designation	Heat Number	Chemistry (Percent)											
		Al	V	Cr	Sn	Zr	Cb	Ta	C	Fe	N_2	O_2	H_2
MG	31372	5.95	3.91	NR	NR	NR	NR	NR	0.02	0.14	0.010	0.137*	0.0049
MG	23142	6.31	3.78	NR	NR	NR	NR	NR	0.03	0.21	0.018	NR	0.0053
MG	23262	6.21	3.81	NR	NR	NR	NR	NR	0.01	0.17	0.011	NR	0.0079
RG-1-4	R11975	5.95	3.90	NR	NR	NR	NR	NR	0.028	0.20	0.012	NR	0.0050
TG-1	M9266	6.40	4.20	NR	NR	NR	NR	NR	0.030	0.14	0.019	NR	0.0040
MD-1-4	32547	5.40	NR	NR	2.64	NR	NR	NR	0.030	0.09	0.009	0.164*	0.0132
MQ-1**	32502-1	8.13	NR	R	NR	NR	2.47*	2.07*	0.02	0.16	0.009	0.078	0.0038
MQ-2	32502-2	8.51	NR	R	NR	NR	2.47	2.07	0.01	0.18	0.006	0.074	0.0041
MQ-3	320502-3	8.08	NR	NR	NR	NR	2.47	2.07	0.08	0.16	0.009	0.079	0.0048
MQ-4	320503-4	8.32	NR	NR	NR	NR	2.47	2.07	0.02	0.17	0.006	0.086	0.0042
TX	V1465	6.15	1.10	NR	NR	3.99	NR	NR	0.029	0.08	0.017	NR	0.007
TV	M9469	2.80	13.70	11.1	NR	NR	NR	NR	0.022	0.20	0.020	0.089	0.0095
CV	F-7335	3.30	13.40	11.0	NR	NR	NR	NR	0.010	0.31	0.030	0.130	0.0118
CVH	F-7335	3.30	13.40	11.0	NR	NR	NR	NR	0.010	0.31	0.030	0.130	0.0094
TA	M9239	NR	NR	NR	NR	NR	NR	NR	0.025	0.11	0.019	NR	0.004

* Ingot Analysis

** Manufacturer's designation for MQ material is MSM-821.

The second letter designates the alloy:*

A - Unalloyed titanium

D - 5Al-2.5Sn

G - 6Al-4V

Q - 8Al-2Cb-1Ta

V - 13V-11Cr-4Al

VH - 13V-11Cr-4Al aged

X - 6Al-4Zr-1V (experimental alloy)

The directions of roll were not identified on all the as-received plates. Oral identifications as to the directions of roll were obtained from the producers who had failed to identify the rolling direction on their plates. The test data reported for a given direction of rolling may not be comparable between producers, since the direction of rolling reported may correspond to the axis of the ingot or to the direction of final rolling.

Detailed data for the various alloys have been requested from the producers. Some producers have complied, but the data received are incomplete. After receipt of all process data, this information and its possible correlation with present and future test results will be published.

The chemistries submitted by the various producers are also somewhat incomplete. Oxygen content for a number of alloys is excluded from most of the submitted analyses. In one case oxygen content was reported from the ingot analysis. It should be understood that, in processing from the ingot to the billet and finally to the plate, oxygen and other interstitials will be picked up.

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* This designation corresponds to the appendix letters in a compilation of the mechanical and physical properties of titanium by Battelle Memorial Institute.[4]

Cylindrical compression specimens 1/2 in. in diameter and 2 in. long were machined in accordance with ASTM standards.[5] Standard 0.252-in.-diameter tensile and standard Charpy V-notch impact specimens (notched perpendicular to the surface of the plate) were machined in accordance with Federal Standards.[6,7] All specimens were taken from the midthickness of the plate in both the longitudinal and transverse directions. A limited number of transverse tensile tests were made for comparative purposes.

Specimens for the drop-weight and explosion crack-starter tests were in accordance with NRL standards for 1-in. thick plate. The drop-weight specimens were 1 in. thick by 3 1/2 in. wide by 14 in. long. The explosion crack-starter plates were 1 in. by 20 in. by 20 in. A brittle weld deposit was welded on each plate or specimen perpendicular to the direction of rolling. Each deposit was notched parallel to the direction of roll to a depth of 0.07 in. from the base plate.

EXPERIMENTAL PROCEDURE

Mechanical property load-strain curves were recorded by an automatic Baldwin-Southwark microformer load-strain recorder attached to a 120,000-lb hydraulic testing machine. A strain magnification of 500 to 1 was used throughout this investigation. Compressive moduli of elasticity were obtained by means of Tuckerman optical strain gages. To avoid any eccentric loading in tension or compression, universal ball-joint attachments were used, and the bearing surface of each compression specimen was coated prior to testing with a mixture of molybdenum disulphide and silicon grease to minimize edge effects.

The few tensile tests at the Model Basin were made at a standard strain rate of 0.003 to 0.007 in/in/min. The compressive strain rates were from 0.0008 to 0.001 in/in/min maintained through the 0.2-percent offset yield load level.

Since submarine design requires that the shell material be able to withstand tensile yielding in the presence of a notch without extensive tearing or cleavage failure, each of the alloys was evaluated for resistance to brittle fracture and to tearing in the presence of a notch. The Charpy V-notch, drop-weight, and explosion crack-starter tests, which are used for measuring the ductile to brittle transition characteristics of steels, were utilized in measuring the fracture transition of the titanium alloys being investigated.

The three critical fracture transition temperatures are defined as follows:[8]

1. NDT, Nil-Ductility Transition - Below this temperature steels show no ability to deform plastically, i.e., percent elongation or reduction in thickness in the presence of a sharp crack is nil.

2. FTE, Fracture Transition for Elastic Loading - Above the NDT temperature steels show notch ductility to the extent that plastic deformation must occur before cracks will be initiated. While fracture <u>initiation</u> is difficult in this range (requires forcing by plastic loading), <u>propagation</u> is "easy" as indicated by the fact that the fractures of the explosion crack-starter plates continue through the lightly loaded edge regions supported by the die. For all steels tested, the FTE temperature marks the temperature above which fracture propagation becomes difficult and the fractures remain entirely within the central bulge regions.

3. FTP, Fracture Transition for Plastic Loading - The FTP temperature marks the temperature above which the explosion test by overloading may tear the steel by shear, but the steel cannot develop brittle fracture. This temperature represents a point of absolute ductility regardless of severity of loading.

Charpy V-notch specimens were tested in a Tinius-Olsen, pendulum-type impact tester with a striking velocity at impact of 16.85 fps. Prior to testing the machine was calibrated in accordance with ASTM standards.[9]

Essentially, in the drop-weight test[10,11] a simple beam type of test specimen is impact loaded in the center by a dropping weight. The drop-weight specimens were tested over a range of temperatures with a 93.5-lb hammer falling from a height of 13 ft. A 0.3-in. stop arrangement in the bottom center of the jig holding the specimen limited deflection of the specimen. The 0.3-in. stop distance used for steel was tentatively selected for the titanium since in the slow bend test described later the titanium brittle weld deposit propagated a crack within this stop distance.

For the explosion crack-starter test, a specimen is placed over a circular 15-in.-diameter female die. A predetermined explosive charge, detonated at a prescribed distance over the plate, exerts a uniform gas pressure on the plate. The specimen is dished or forced into the open circular hole by this charge. The resulting type of fracture and its extent determines the three critical fracture transition temperatures: NDT, FTE, and FTP.[12]

The Bureau of Ships authorized that the explosion crack-starter tests be performed at the Naval Weapons Laboratory, Dahlgren, Virginia.[13] These tests were performed as directed with the temperatures of the tests and the explosive charges prescribed by the Bureau of Ships and the Model Basin. The same standard of reduction in thickness in the bulged area as used for steel, 3 to 5 percent, was used in selecting the charge for the explosion crack-starter tests. A 7-lb charge with a 15-in. standoff distance was used. The charge originally selected was 8 lb but, since the test plate demonstrated excessive reduction in thickness in the bulged area, the charge was reduced to 7 lb.

For both the drop-weight test and explosion crack-starter test, a brittle weld deposit had to be developed to propagate a sharp crack into the base metal as soon as the region of the plate underneath the weld yields plastically. The hard-surfacing weld deposit used on steel was unsuitable for the titanium alloys because of its higher modulus and lack of alloying compatibility.

The weld deposit had to have alloying compatibility and elastic characteristics similar to the base metal being investigated. Such a weld deposit was obtained by depositing a one-pass titanium weld bead contaminated with nitrogen. The welding was done automatically by means of inert-gas machine welding techniques. This setup is shown in Figures 2 and 3. The drop-weight specimen is set into an enclosed metal box for depositing the weld bead, while on the crack-starter plate, a small box with an open bottom is set over the test plate and sealed to the test plate with modelmaker's clay. Both boxes have sliding tops through which the welding gun is set. A positive pressure of helium was passed into the chamber of the boxes; during the welding sequence a mixture of helium and the contaminating gas nitrogen, 30 percent by volume, was passed through the gun. The weld deposit was laid with a 0.045-in.-diameter A-70 titanium wire and a heat input of 18,000 joules/in.

Metallographic analysis of the base material underlying the contaminated weld deposit revealed that the weld deposit penetrated approximately 1/16 in. into the base plate. The heat-affected zone surrounding the weld deposit extended about 1/8 in. Microhardnesses indicated that the contaminating nitrogen did not penetrate into the heat-affected zone of the base material. There was a sharp demarcation in hardness between the penetrated weld and the heat-affected zone.

In order to evaluate the notch-propagating characteristics of the contaminated titanium deposit, a slow bend test

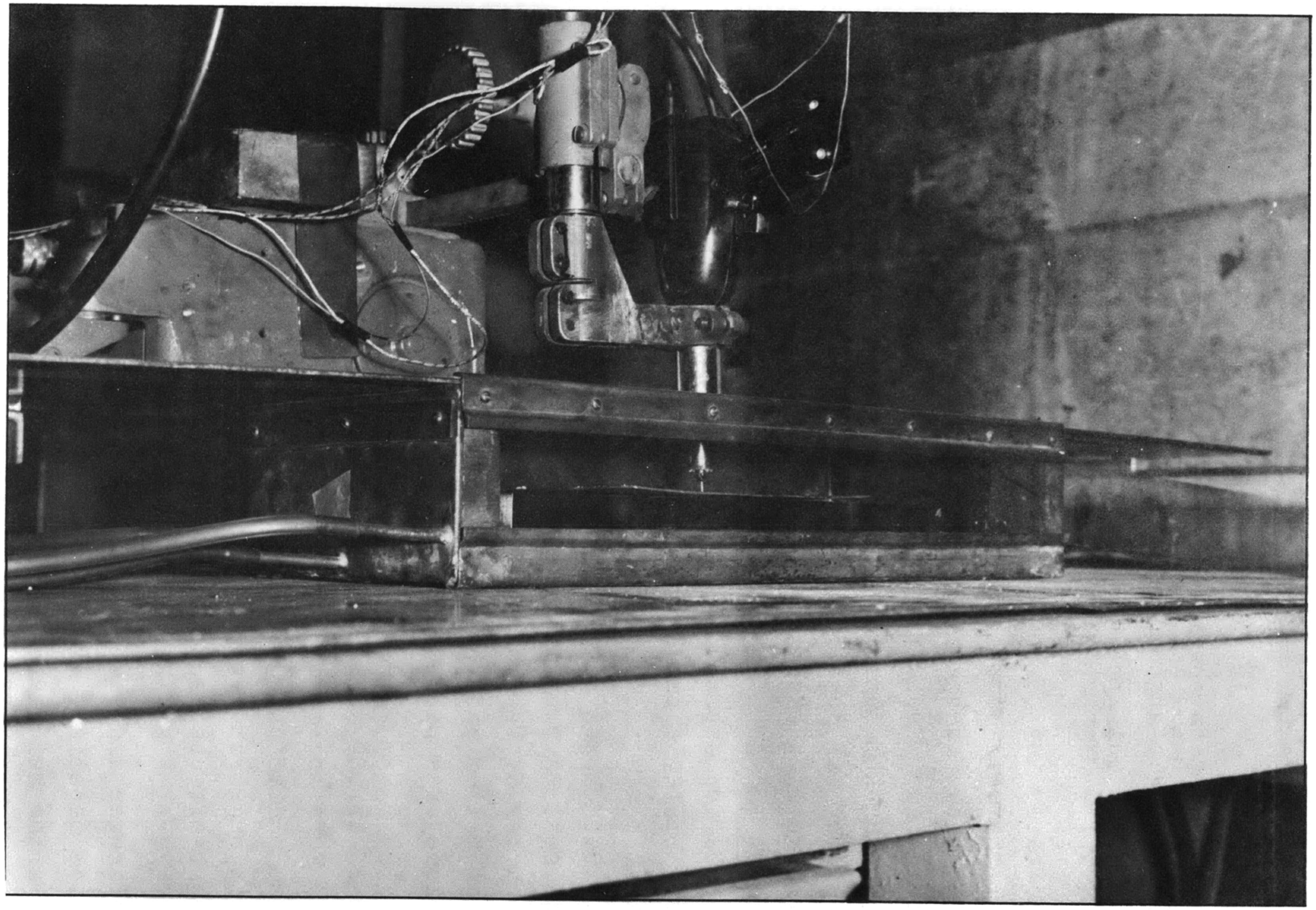

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Figure 2 - Welding Setup for Depositing Brittle Bead on Drop-Weight Test Specimens

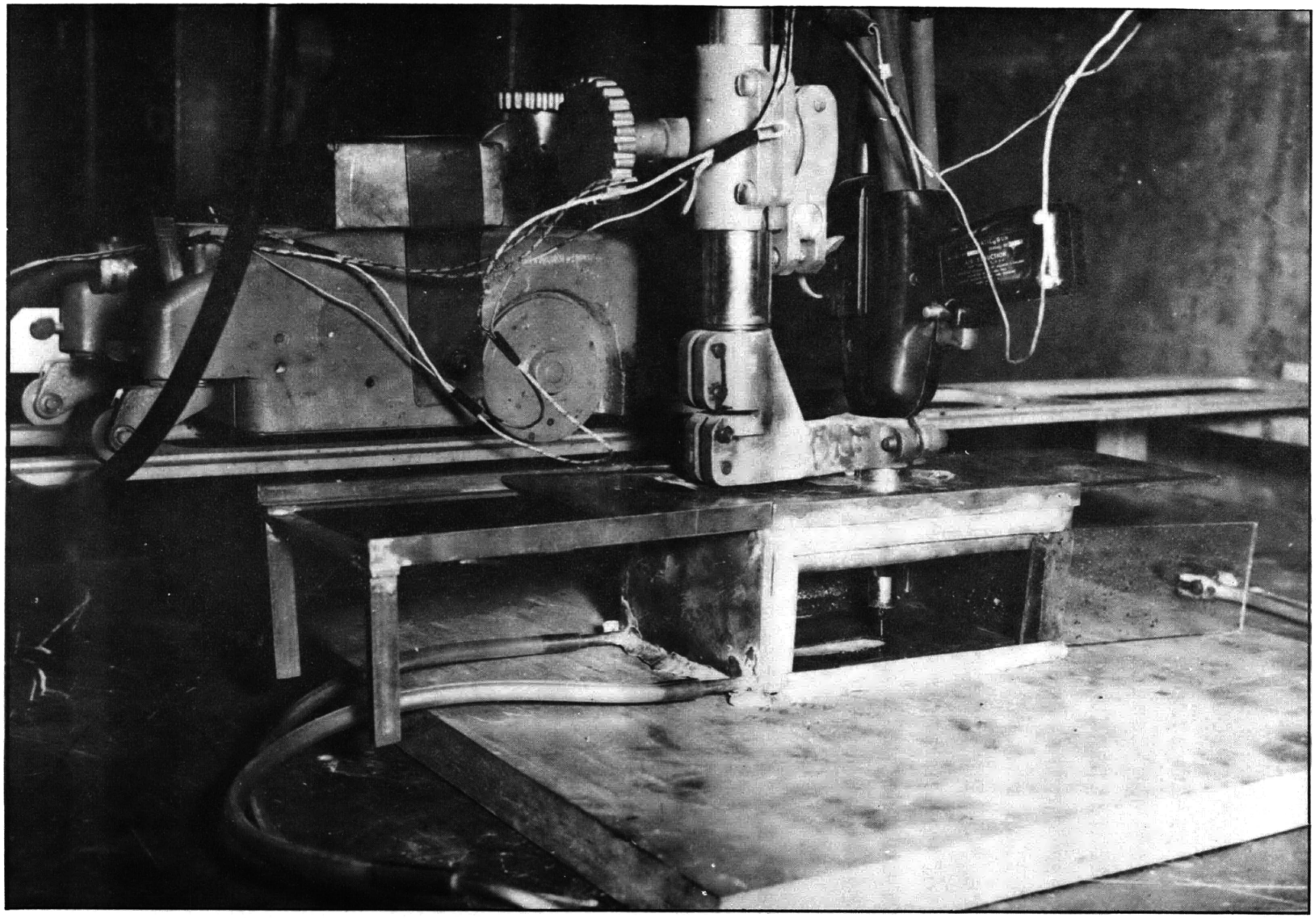

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Figure 3 - Welding Setup for Depositing Brittle Bead
on Explosion Crack-Starter Test Plate

was made on two specimens similar to those used in the drop-weight test. One specimen, a TA alloy, had a tensile yield strength of 49,000 psi, and the other, an RG alloy, had a tensile yield strength of 120,000 psi. Photostress was used to depict the loadpoint at which a cleavage crack would start to propagate from the notched weld. The bending of the beam during loading was recorded automatically on a load-deflection recorder attached to the testing machine; see Figure 4. The recorded deflections of the bend specimen at time of crack propagation were 0.2 in. or less. The crack began in the weld deposit simultaneously with the yielding of the base material.

A question may arise as to the validity of propagating a crack into the base metal by utilizing a brittle weld deposit. The weld deposit may or may not embrittle a small portion of the heat-affected zone, that is, embrittling may be due to the contaminating gas or to phase change during the welding sequence. The latter aspect can be discounted, for the material selected for submarine hull construction would have to withstand embrittling by welding heat-input. Micro-hardness and metallographic analysis do not reveal or indicate any diffusion of the nitrogen in the base metal or embrittlement of the base metal during the welding sequence.

Metallographic specimens were mounted in a plastic room-setting epoxy resin. After the specimens were mounted, 1/4 in. of specimen surface was machined off under coolant to remove any cold-worked areas. The surfaces were then progressively ground by hand on 180-, 240-, 400-, and 600-grit silicon-carbide papers. Final polishing was performed in two stages utilizing a 60-cycle automatic vibrating polisher. In the semifinal polishing, the bowl mounting plate was covered with a bleached silk cloth, and a slurry of Linde A, distilled water, and aerosol was used. Gamal cloth covered

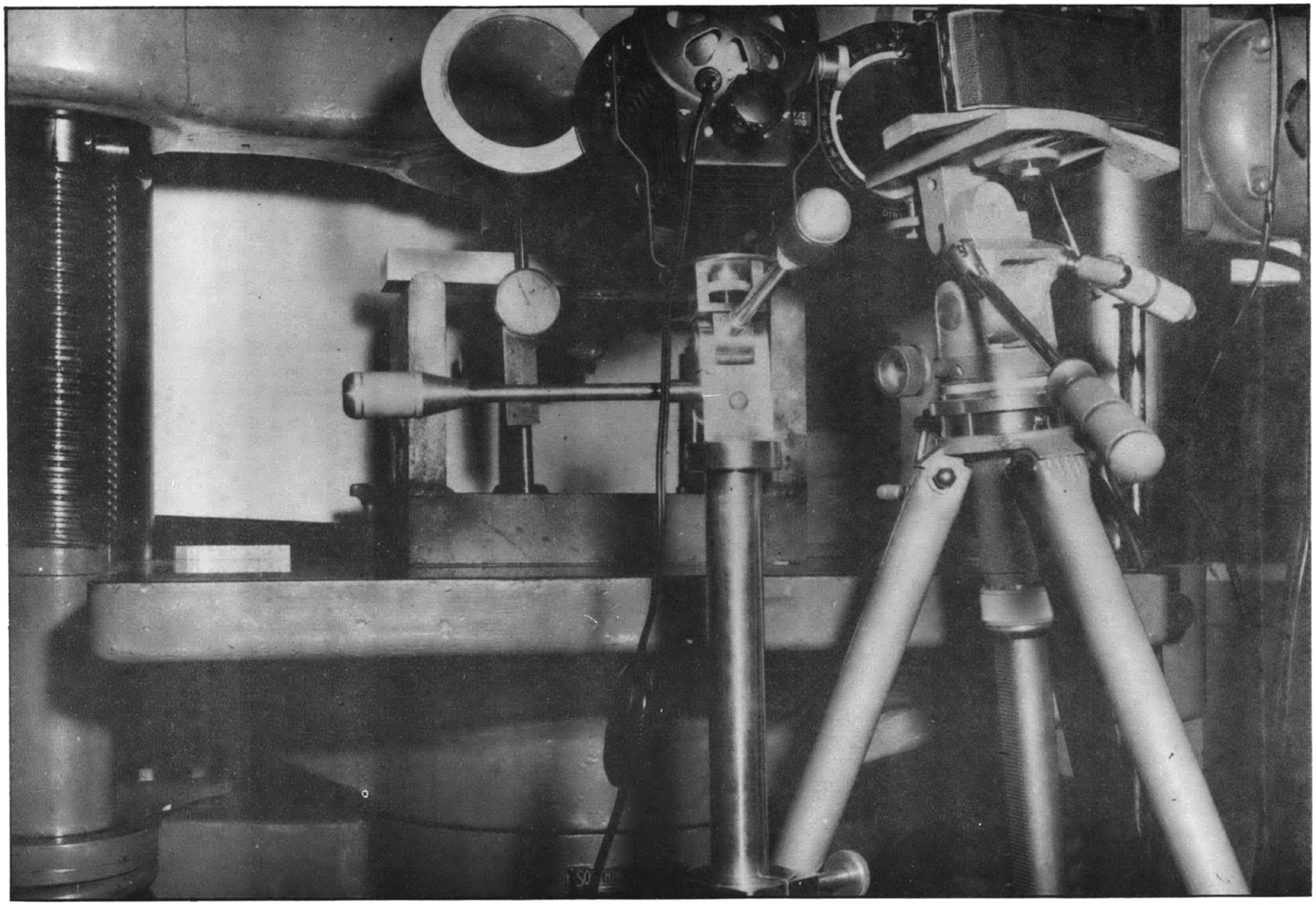

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Figure 4 - Test Setup for Evaluating Notch Propagating Characteristics of an Embrittled Titanium Weld Deposit

with a slurry of Linde B, distilled water, and aerosol was used for the final polishing operation.

A solution of 2-percent hydrofluoric acid, 4-percent nitric acid, and water was used as a general etchant.

Macrograin sizes were taken in accordance with ASTM standards.[14] Both the intercept and planimetric methods were employed. Where possible, the macrograin sizes were compared with the micrograin sizes.

Dead-weight room-temperature compressive creep studies are presently underway at the Bureau of Standards. SR-4 strain gages and automatic continuous strain-recording equipment are being used to obtain creep rates. Creep loads are set at 0.8 of the yield strength of the specimen.

TEST RESULTS

TENSILE AND COMPRESSION TESTS

Table 2 lists the mechanical property data reported by the various producers and, for comparative purposes, the results of transverse tensile tests made by the Model Basin for a number of the alloys. Since compressive yield strengths are used as the criteria in submarine design, longitudinal and transverse compressive yield strengths were obtained at strain rates duplicating those used in submarine model tests. Care should be taken in comparing the reported tensile yield strengths with the compressive yield strengths since the yield strengths obtained can only be considered nominal for a given testing procedure because titanium alloys are known to be strongly rate-sensitive.[15]

RATE-OF-LOADING TEST

A cursory review of the literature did not indicate that compressive strain-rate studies had been made. In this study on the effects of rate of loading on the compressive yield strength of titanium alloys, it is realized that a

TABLE 2

Comparison of Mechanical Properties of Titanium Alloys from Producers' and DTMB Analysis

Alloy Designation		Producers' Properties				DTMB Results					
		Ultimate Strength psi	Tensile Yield Strength (0.2%) psi	Percent Elongation in 2 Inches	Percent Reduction in Area	Ultimate Strength psi	Tensile Yield Strength (0.2%) psi	Compressive Yield Strength (0.2%) psi	Percent Elongation in 1 Inch	Percent Reduction in Area	Compressive Modulus of Elasticity $\times 10^6$ psi
MG	L	142,000	131,000	11	NR	-	-	133,000	-	-	17.9
(6Al-4V)	T	136,000	120,000	11	NR	-	-	122,000	-	-	17.7
RG	L	-	-	-	-	-	-	122,000	-	-	17.1
(6Al-4V)	T	-	-	-	-	130,000	110,000	114,000	14	34	17.0
TG	L	141,000	136,000	14	32	-	-	-	-	-	-
(6Al-4V)	T	138,000	129,000	14	31	-	-	-	-	-	-
MD	L	135,000	123,000	11	NR	-	-	117,000	-	-	17.5
(5Al-2.5Sn)	T	144,000	132,000	11	NR	147,000	129,000	153,000	8	14.5	-
MQ	L	123,000	114,000	13.5	32.5	-	-	118,000	-	-	-
(8Al-2Cb-1Ta)	T	131,000	119,000	13.0	19.0	-	-	130,000	-	-	-
TX	L	145,000	138,000	17*	34.5	-	-	135,000	-	-	17.2
	T	144,000	136,000	17*	38.0	-	-	140,000	-	-	17.8
TV	L	131,000	129,000	24.5*	25.4	-	-	124,000	-	-	14.8
	T	133,000	127,000	24.0*	25.2	129,000	121,000	120,000	9	38.4	14.4
CV	L	136,000	135,000	12.5	25.4	-	-	120,000	-	-	14.4
	T	140,000	137,000	10.2	25.2	137,000	126,000	127,000	7	14.6	15.1
CVH		155,000	152,000	6.4	7.1	-	-	151,000	-	-	-
		NR	NR	NR	NR	-	-	-	-	-	-
TA	L	73,000	55,000	30.5*	51	-	-	51,000	-	-	16.3
(Unalloyed)	T	74,000	56,000	33.0*	51	70,000	49,000	49,000	22	51	16.8

* One-inch gage.

uniform strain rate has to be maintained to reflect the differences in strength levels. Unfortunately, the hydraulic testing machines available at the Model Basin are not at present equipped with automatic strain-rate controls.

In order to obtain a qualitative indication of the effects of rate of loading, the rate in pounds per second was kept as constant as the operator's skill would permit. The rate of loading of four alloys is reported in Table 3 and depicted for three alloys in Figure 5. The load rates given are averages over a 5000-psi stress range within the plastic yielding range. The strain rates are not to be considered constant since the inertia of the machine and recorder and the possible spring effect of the testing machine columns must be taken into account. The data obtained from each of the alloys are comparable since the rates of loading and test conditions for each test are within experimental differences.

The MD (5Al-2.5Sn) alloy indicates the greatest response to rate of loading. The RG (6Al-4V) alloy also shows a marked increase in compressive yield strength with increasing loading rate; with rates of loading exceeding 8 ksi/sec, the yield strength approaches an asymptote. The MQ (8Al-2Cb-1Ta) alloy showed the least response to loading rates.

An interesting phenomenon was observed in testing an MD (5Al-2.5Sn) alloy at a fast rate of loading, 25 ksi/sec. After the specimen was loaded rapidly in the plastic range and the load cell was unloaded rapidly, the specimen explosively broke at a load approximately 90 percent of the yield load. The resulting fracture occurred along a 45-deg plane, as shown in Figure 6. Complete studies of this phenomenon are planned.

CHARPY V-NOTCH TEST

Conventional Charpy V-notch energy-temperature curves are plotted in Figures 7 through 14. As a measure of ductility,

(Text continued on page 28)

TABLE 3

Variation of Yield Strength with Compressive Rate of Loading for Submitted Titanium Alloys

Rate of Loading in Yield Region ksi sec	Yield Strength (0.2%), ksi									
	TA Unalloyed	MD 5Al-2.5Sn	MG 6Al-4V	RG 6Al-4V	TG 6Al-4V	MQ 8Al-2Cb-1Ta	CV 13V-11CR 4-Al	CVH 13V-11CR 4-Al	TV 13V-11Cr 4-Al	TX 6Al-4Zr-1V
0.0008 - 0.001	51	117	133	122	-	118	120	151	124	135
0.02 - 0.04	-	163	-	145	-	130	-	-	-	-
4.0 - 5.0	-	187	-	166	-	137	-	-	-	-
8.0 -10.0	-	-	-	184	-	-	-	178	-	-
20.0 -30.0	-	213	-	184	-	141	-	-	-	-

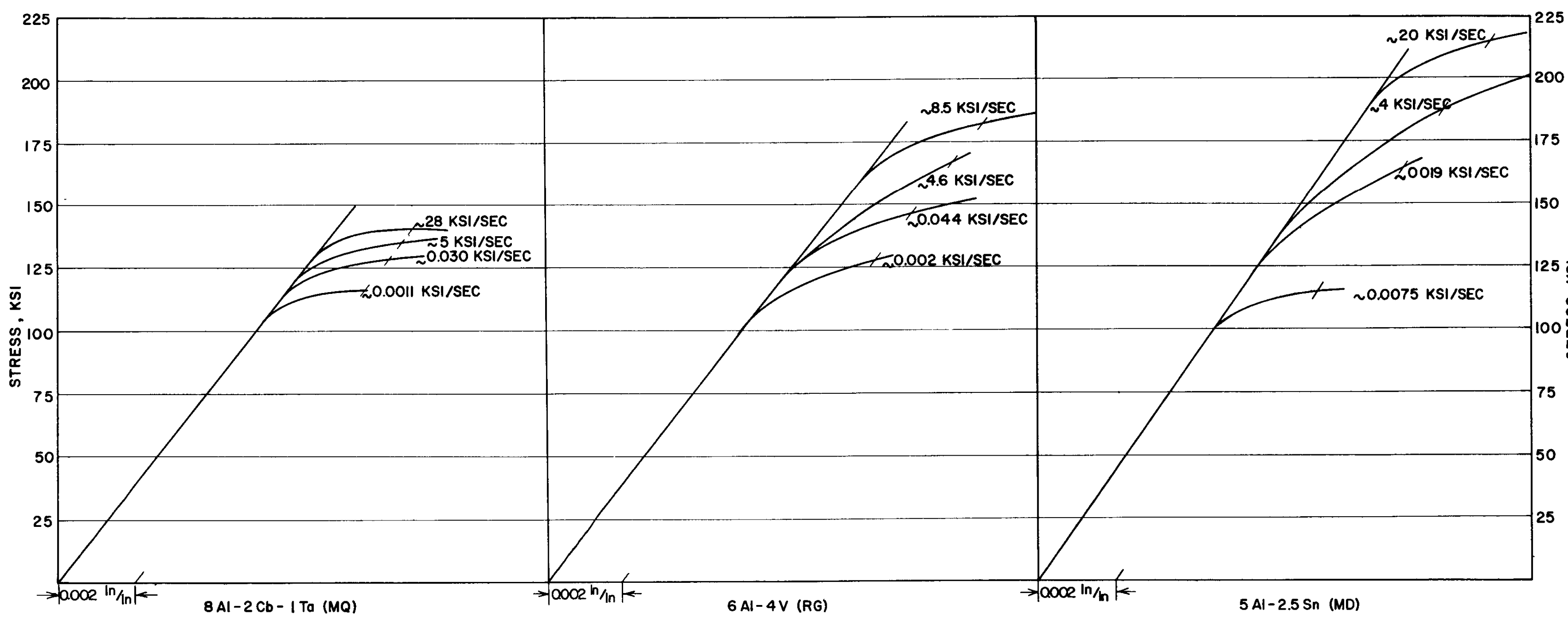
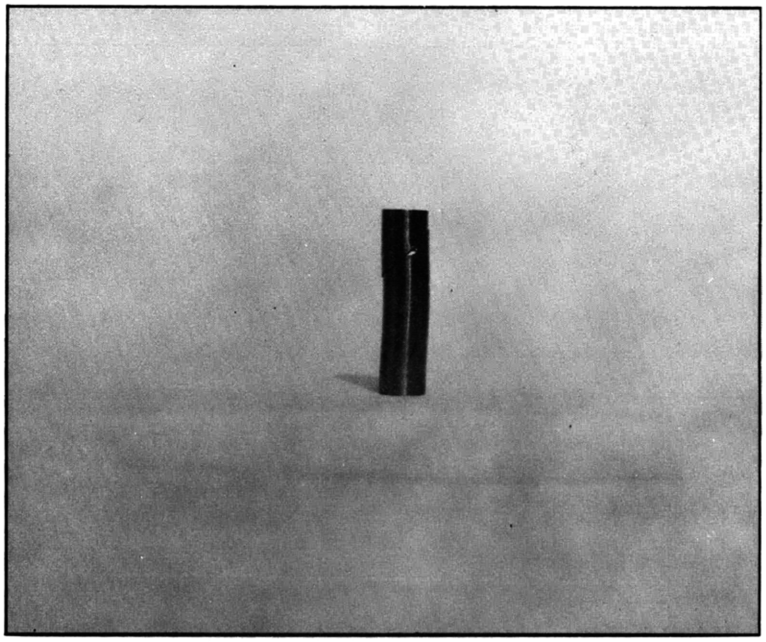


Figure 5 - Effects of Rate of Loading in Compression on Three Titanium Alloys



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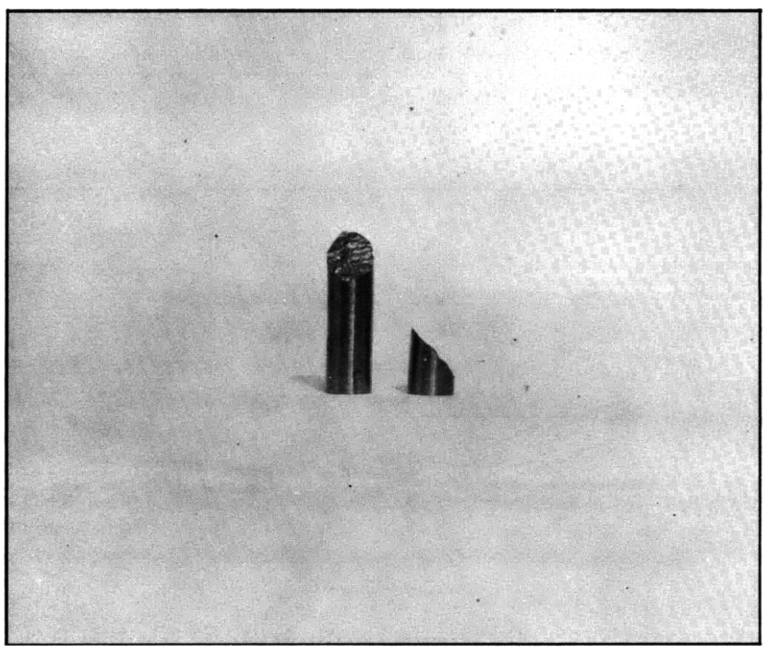

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Figure 6 - Compression Failure of 5Al-2.5Sn (MD) Alloy Resulting from Rapid Loading

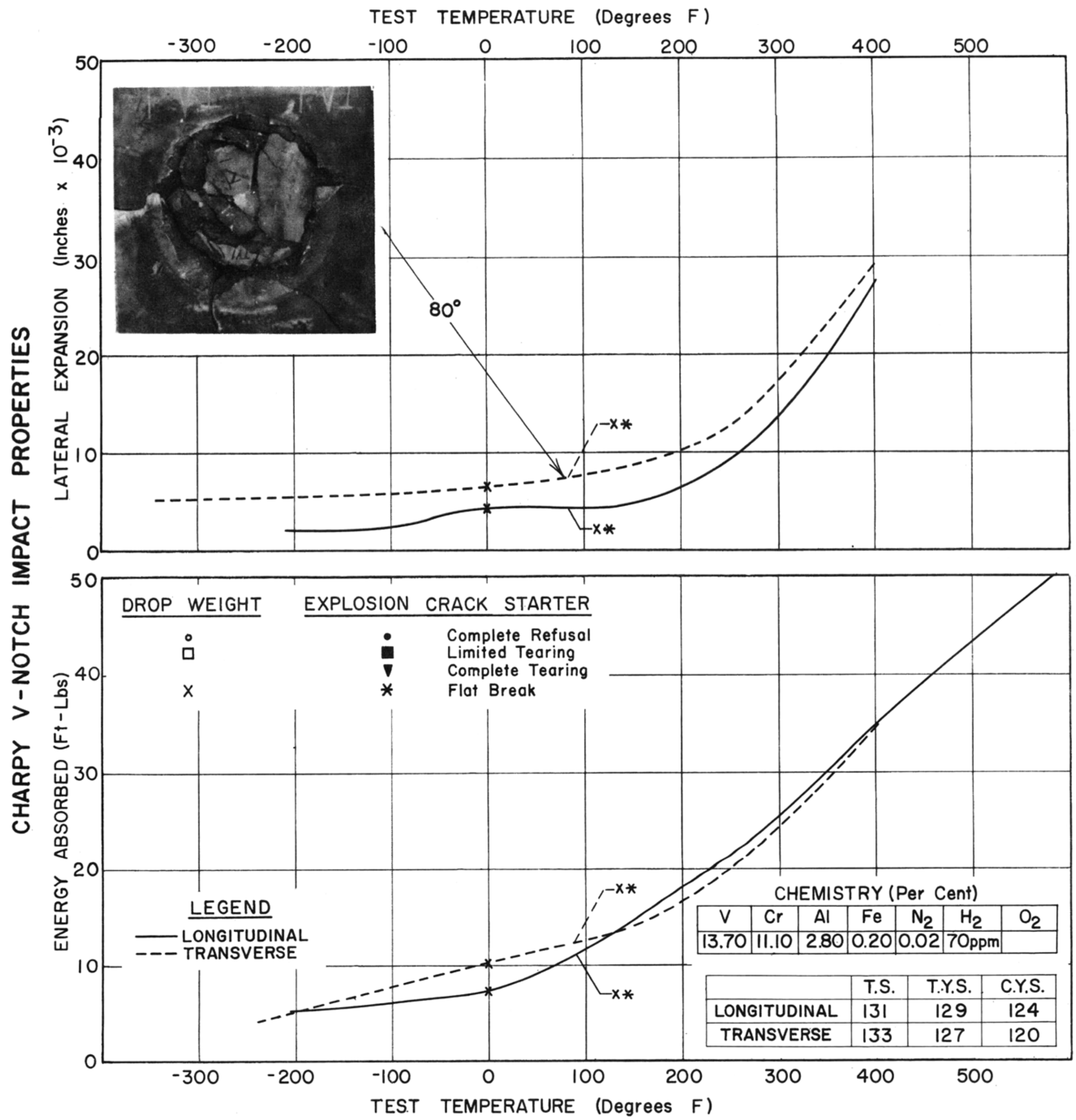


Figure 7 - Comparative Drop-Weight and Explosion Crack-Starter Data Fitted to Charpy V-Notch Curve for 13V-11Cr-4Al (TV)

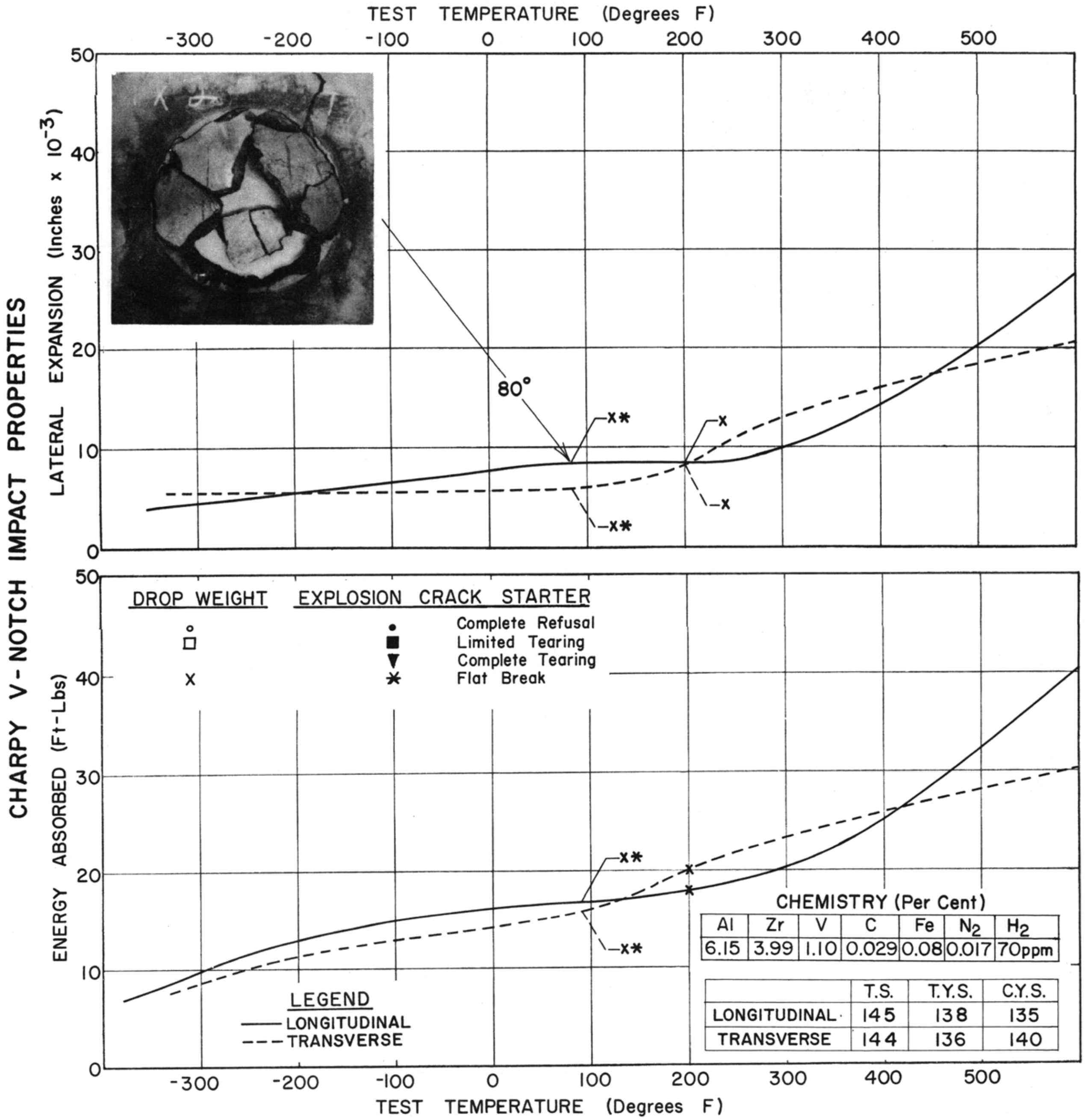


Figure 8 - Comparative Drop-Weight and Explosion Crack-Starter Data Fitted to Charpy V-Notch Curve for 6Al-4Zr-1V (TX)

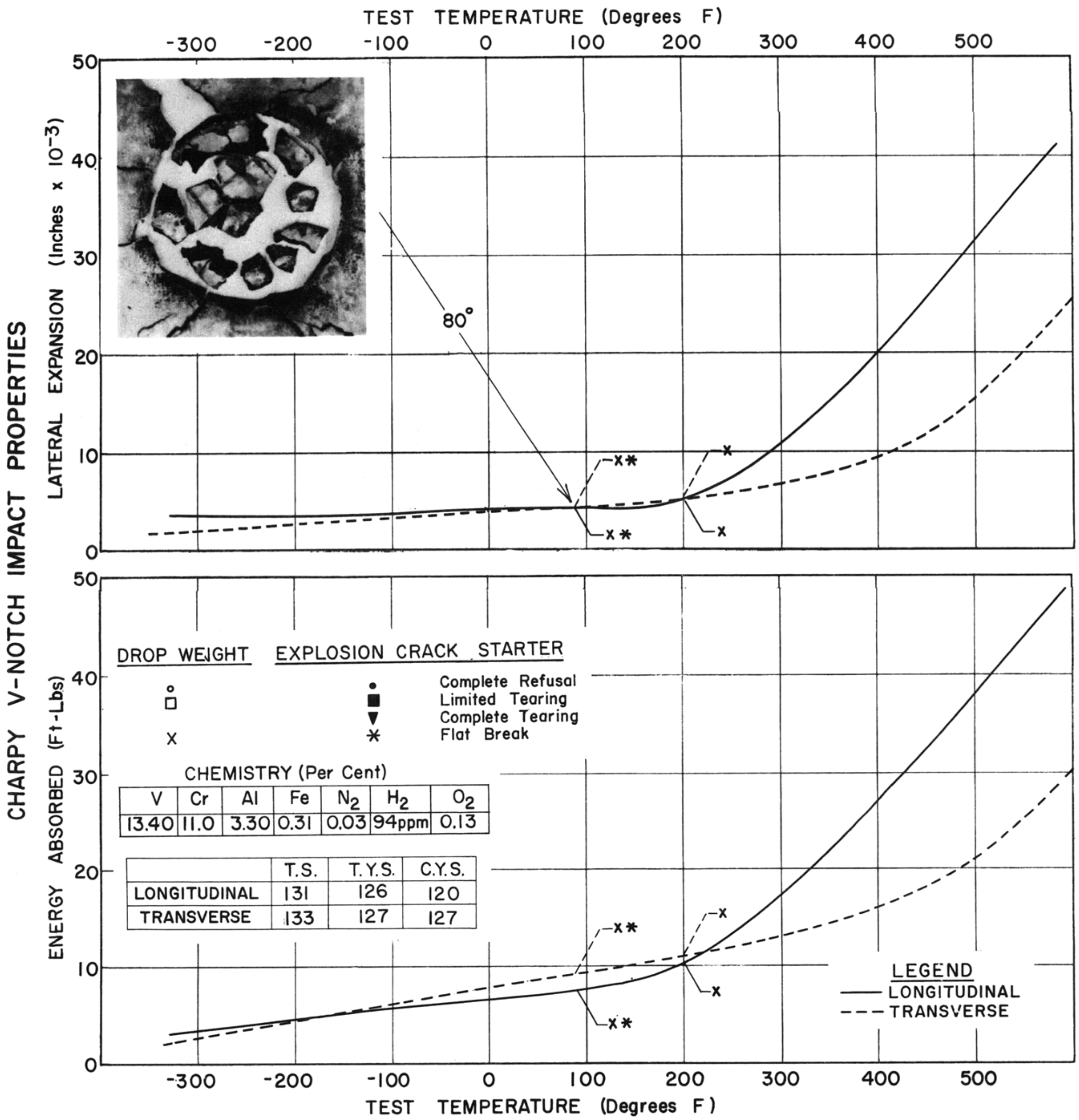


Figure 9 - Comparative Drop-Weight and Explosion Crack-Starter Data Fitted to Charpy V-Notch Curve for 13V-11Cr-4Al (CV)

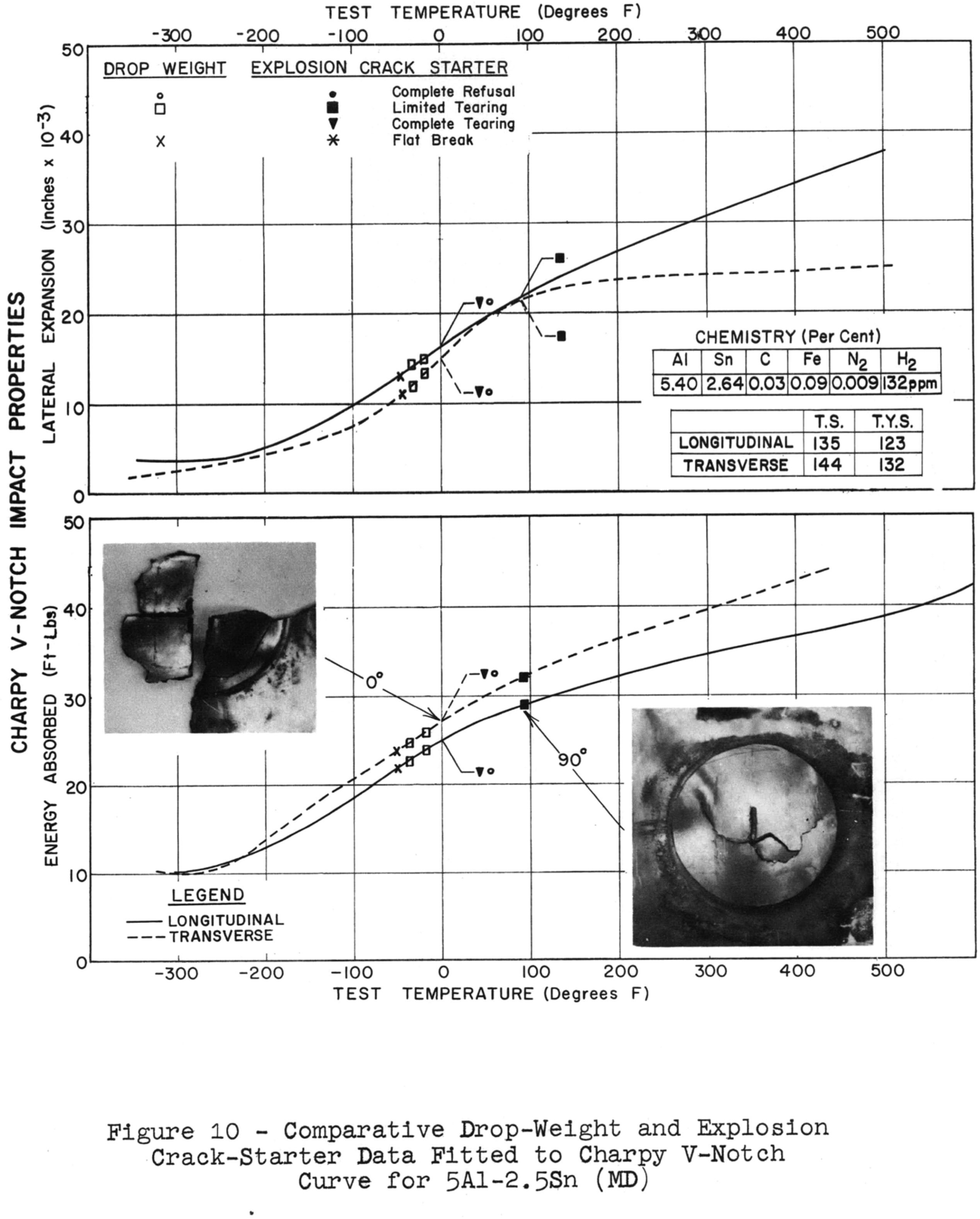


Figure 10 - Comparative Drop-Weight and Explosion Crack-Starter Data Fitted to Charpy V-Notch Curve for 5Al-2.5Sn (MD)

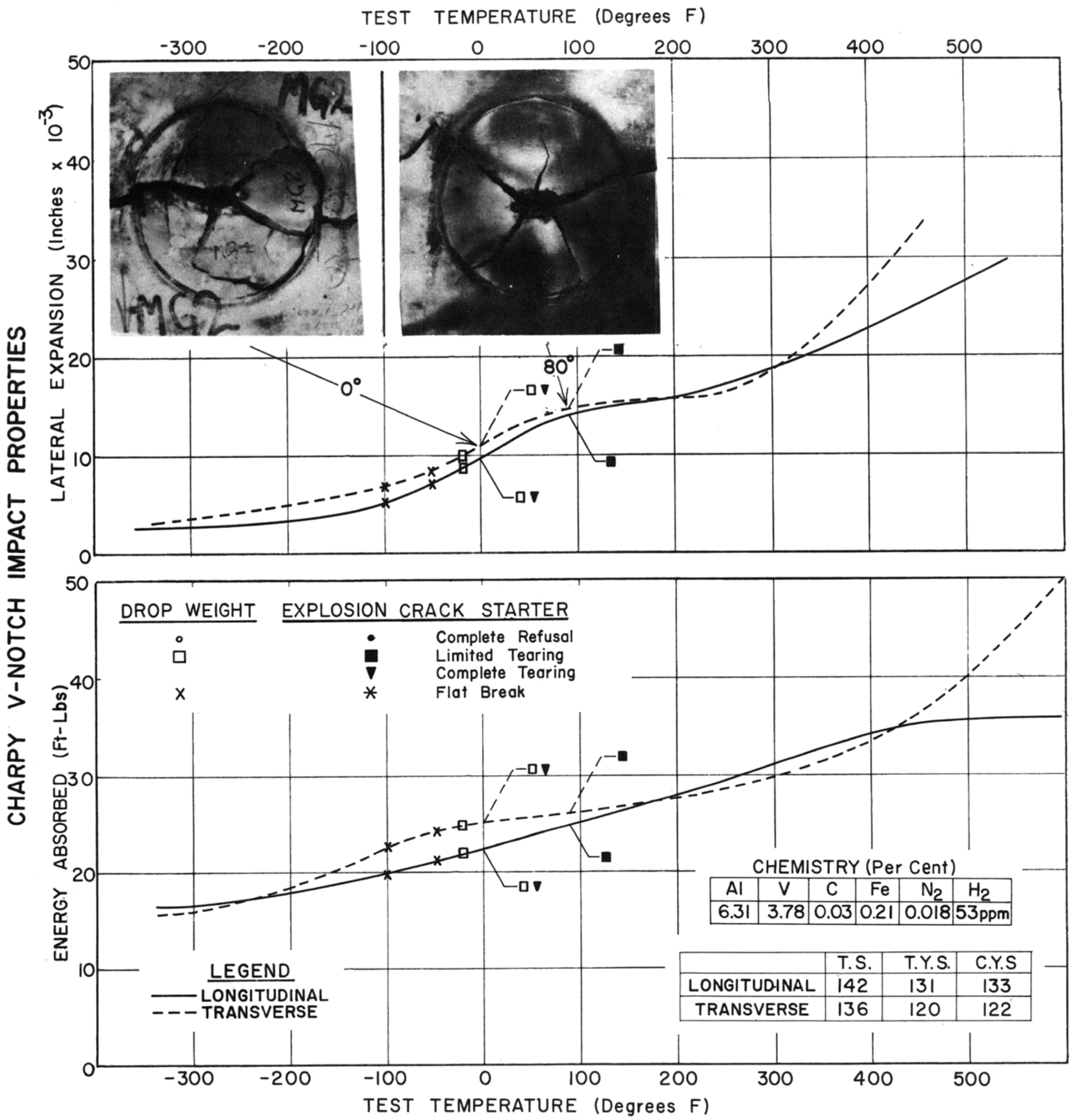
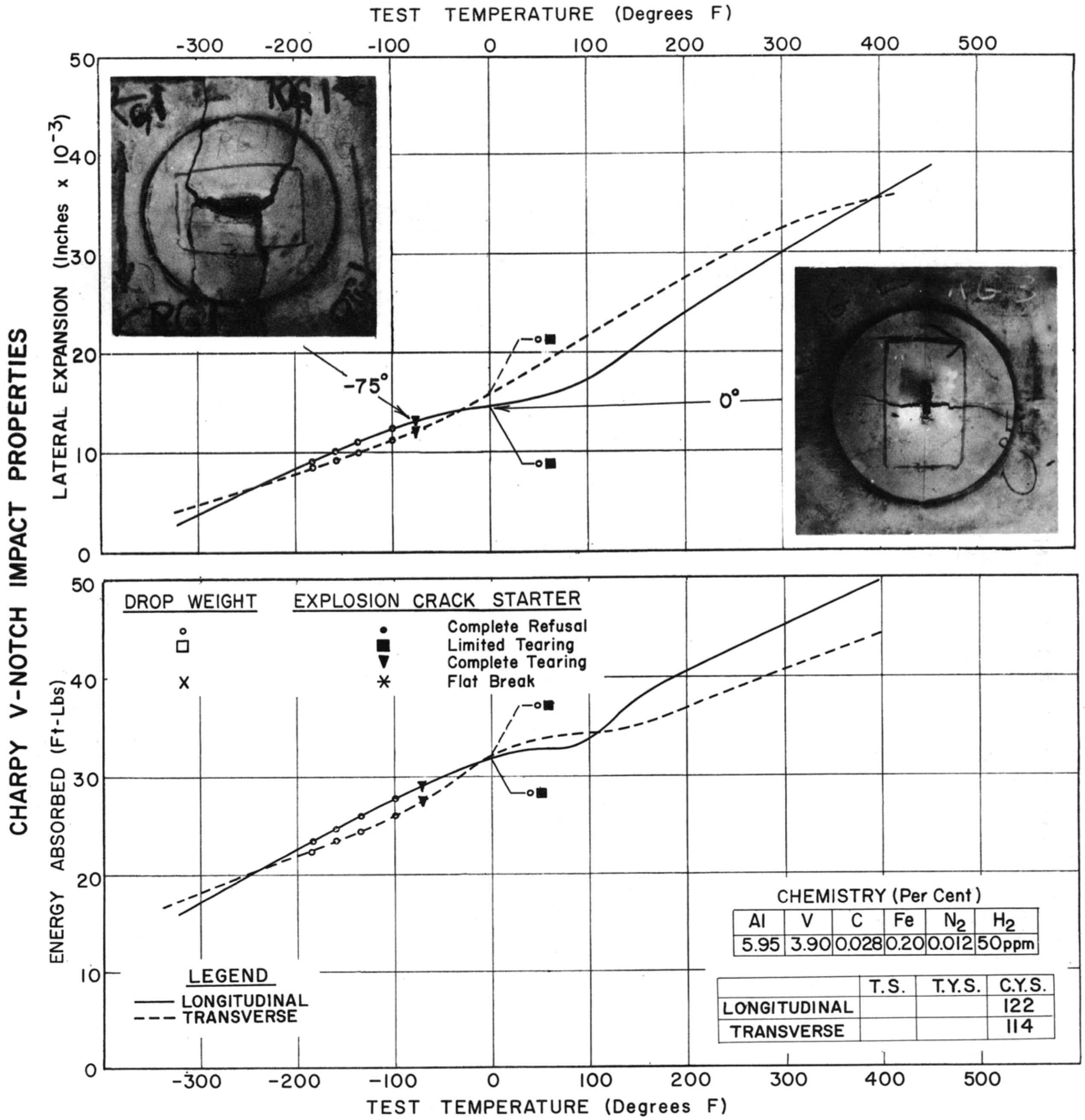


Figure 11 - Comparative Drop-Weight and Explosion Crack-Starter Data Fitted to Charpy V-Notch Curve for 6Al-4V (MG)



Al	V	C	Fe	N_2	H_2
5.95	3.90	0.028	0.20	0.012	50ppm

	T.S.	T.Y.S.	C.Y.S.
LONGITUDINAL			122
TRANSVERSE			114

Figure 12 - Comparative Drop-Weight and Explosion Crack-Starter Data Fitted to Charpy V-Notch Curve for 6Al-4V (RG)

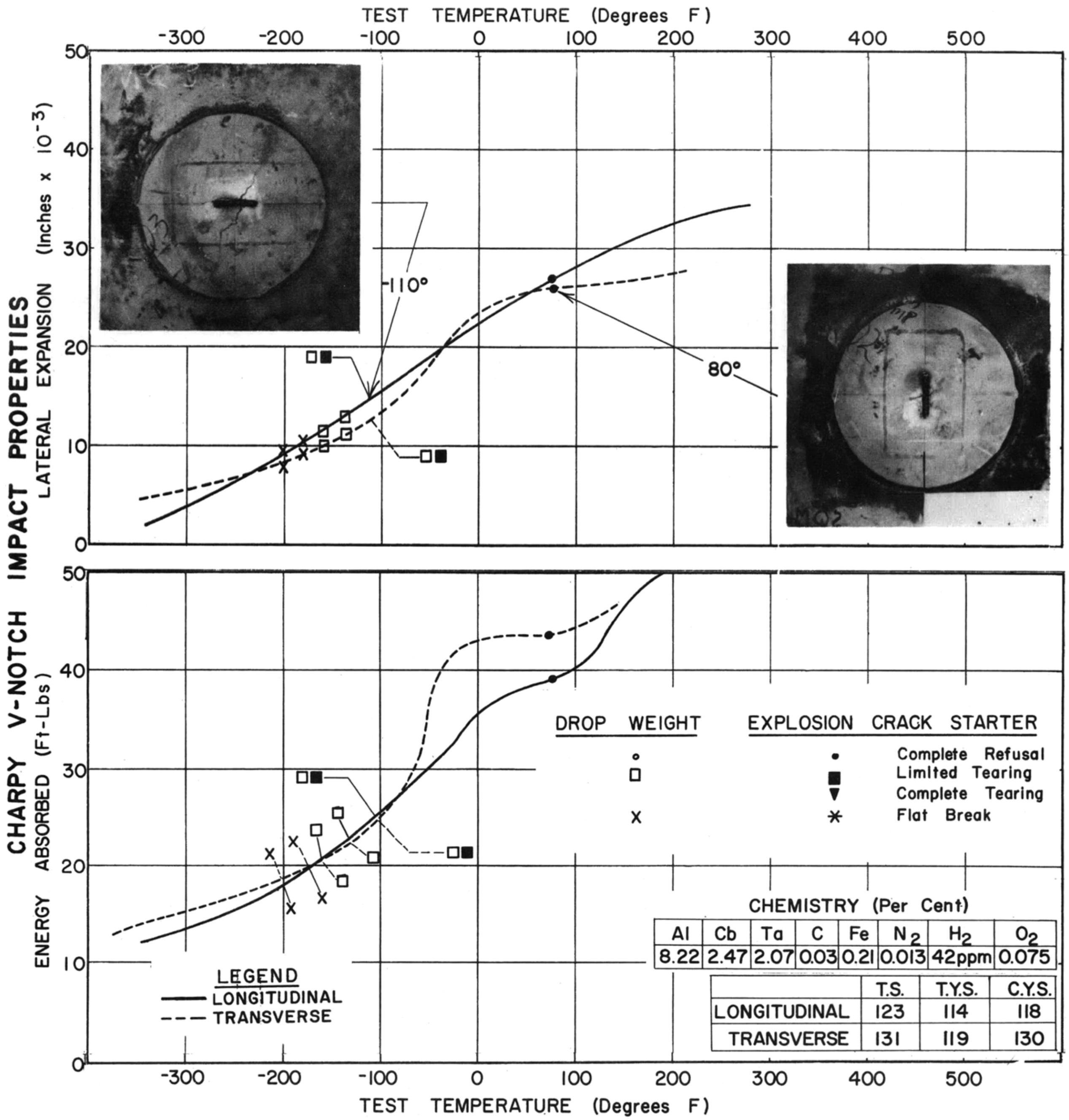


Figure 13 - Comparative Drop-Weight and Explosion Crack-Starter Data Fitted to Charpy V-Notch Curve for 8Al-2Cb-1Ta (MQ)

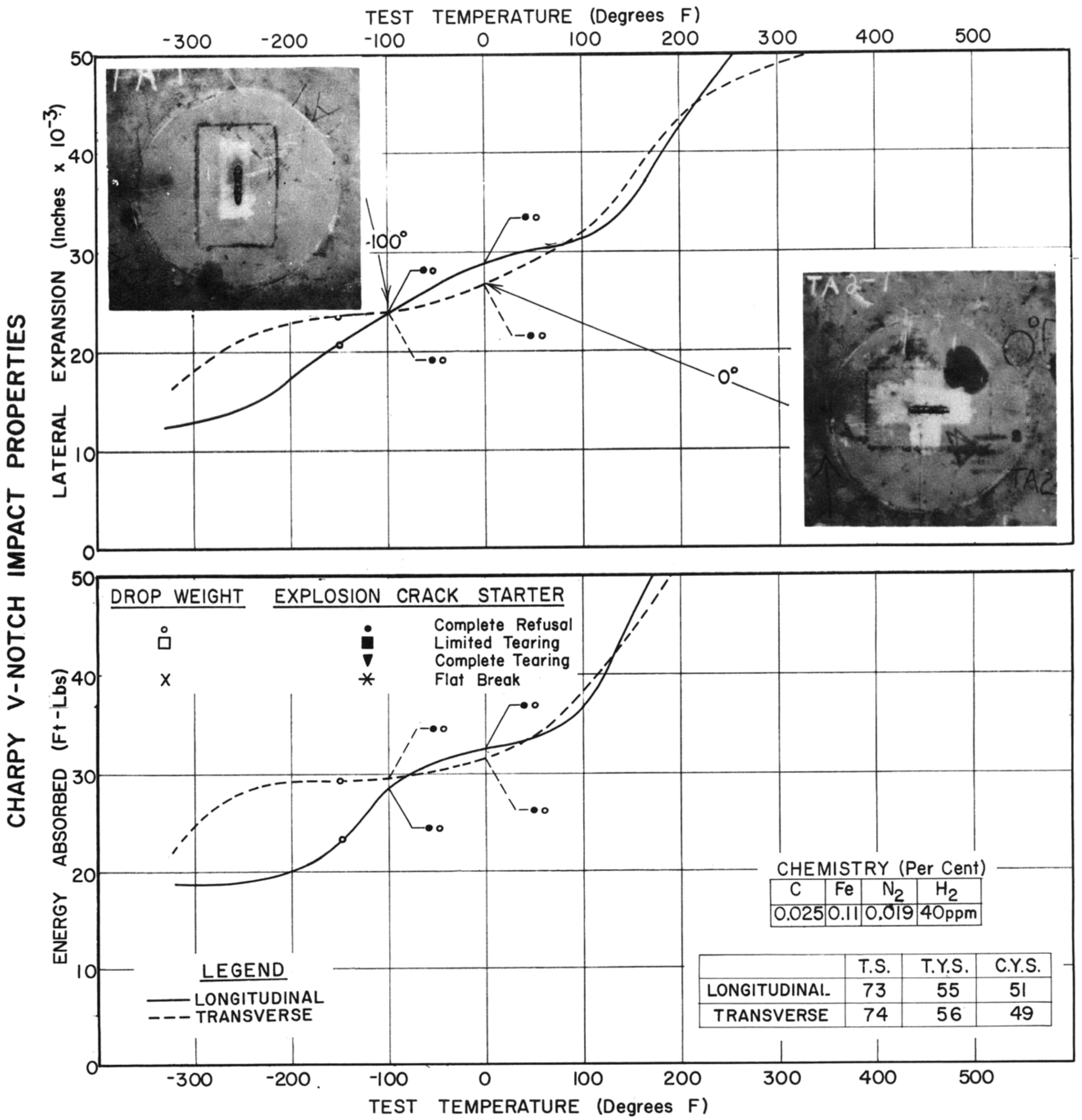


Figure 14 - Comparative Drop-Weight and Explosion Crack-Starter Data Fitted to Charpy V-Notch Curve for Unalloyed Titanium (TA)

the lateral expansion of the specimens at test temperatures are also plotted on the same curves, that is, expansion is measured at the point of impact on the compression side of the broken impact specimen. The energy-absorption-temperature curves, in general, do not show a definite region of transition. The lateral expansion curves for most of the alloys are similar to the energy-absorption data.

DROP-WEIGHT TEST

The drop-weight test defines the highest temperature at which fracture is complete without plastic deformation. However, some doubt was expressed whether the titanium alloys will exhibit a nil-ductility transition (NDT) temperature in the drop-weight test, as does steel.[16] Since the drop-weight tests were going to be compared with the Charpy V-notch test curves and explosion crack-starter test results, it was felt that the validity of this test would either be substantiated or negated. Besides, since the number of crack-starter explosion plates was limited, it was expected that the drop-weight results would give a guide to the temperatures for testing these plates for obtaining the optimum amount of data. An arbitrary NDT temperature of -80 deg F, based on the performance of HY-80 steels, was selected for defining fracture requirements. The results of these tests are depicted as open symbols on the Charpy V-notch curves, Figures 7 through 14.

Although limited tearing has no real significance in the drop-weight tests, it is included in Table 4 and Figures 7 through 14 to indicate crack propagation from the brittle weld into the test specimen. The stop distance used affects the extent of tearing. Use of a stop distance greater than the 0.3 in. used would have propagated the crack into the base material to a greater extent or even have torn the bar in half. A specimen torn in half with permanent deformation does not indicate that the specimen was at its NDT temperature, for NDT

TABLE 4

Results of Drop-Weight Tests

TMB Designation	Alloy	Drop-Weight Results: Test Temperature deg F	Drop-Weight Results: Fracture Characteristic	Drop-Weight Results: Shear Lip, in.	Charpy V-Notch Properties: Energy Absorption: Longitudinal	Charpy V-Notch Properties: Energy Absorption: Transverse	Charpy V-Notch Properties: Lateral Expansion: Longitudinal	Charpy V-Notch Properties: Lateral Expansion: Transverse
TA	Unalloyed	0	Complete Refusal	-	32.5	31.5	28.5	27.0
		-100	Complete Refusal	-	28.5	29.0	24.0	24.0
		-150	Complete Refusal	-	23.0	29.0	20.5	24.0
MD	5Al-2.5Sn	0	Complete Refusal	-	25.5	27.0	16.0	15.0
		-20	Limited Tearing	-	24.0	25.5	15.0	13.0
		-30	Limited Tearing	-	23.5	25.0	14.0	12.0
		-40	Broke	0.08	23.0	24.0	13.5	11.5
MG	6Al-4V	0	Limited Tearing	-	22.5	25.0	9.5	11.0
		-20	Limited Tearing	-	22.0	25.0	8.5	10.0
		-50	Broke	0.310	21.0	24.5	7.0	8.5
		-100	Broke	0.260	20.0	22.5	5.0	7.0
RG	6Al-4V	0	Complete Refusal*	-	31.5	32.0	14.5	16.0
		-100	Complete Refusal*	-	27.5	26.0	12.0	11.2
		-140	Complete Refusal*	-	25.5	24.0	10.8	9.8
		-160	Complete Refusal*	-	24.5	23.5	10.0	9.0
		-180	Complete Refusal*	-	23.5	22.8	9.0	8.5
		-180**	Complete Refusal*	-	23.5	22.8	9.0	8.5
MQ	8Al-2Cb-1Ta	-110	Limited Tearing	-	25.0	24.5	14.5	12.0
		-140	Limited Tearing	-	22.5	22.0	13.0	11.0
		-160	Limited Tearing	-	21.0	21.0	11.5	10.0
		-180	Broke	0.490	19.5	20.0	10.0	9.0
		-200	Broke	0.480	18.0	19.0	9.0	8.0
CV	13V-11Cr-4Al	200	Broke	0	10.5	11.0	5.5	5.0
		90	Broke	0	7.5	9.5	4.5	4.5
TV	13V-11Cr-4Al	85	Broke	0.050	11	12.5	4.5	7.5
		0	Broke	0	7.5	10.5	4.5	6.5
TX	6Al-4Zr-1V	200	Broke	0.20	18.0	20.0	8.5	8.5
		85	Broke	0	17.0	15.5	8.5	6.0

* Results questionable.
** Retest of -180 deg F specimen. Stop distance increased to 0.5 in. and drop distance increased to 14 ft.

temperature is fracture without visible deformation. The results are presented in Table 4.

The CV (13V-11Cr-4Al) and TX (6Al-4Zr-1V) alloys broke at testing temperatures of 210 deg F and 80 deg F with no evidence of permanent deformation. The TV alloy broke at both 80 deg F and 0 deg F. The MD (5Al-2.5Sn) and MG (6Al-4V) alloys broke at temperatures between -40 deg F and -20 deg F. MQ (8Al-2Cb-1Ta) showed limited tearing down to -160 deg F and broke at -180 deg F. TA (unalloyed) did not tear at -150 deg F, while RG (6Al-4V) did not tear at -180 deg F; neither alloy was tested at a lower temperature. Comparison of the Charpy V-notch curve of the RG alloy with the curves of other titanium alloys indicates that the RG alloy should have broken near -100 deg F. Examination of the test specimens showed that the original plate was deformed, and the weld was inadvertently laid on the convex side thereby reducing the stop distance and hence not producing the plastic deformation required for initiating a crack in the weld deposit.

From Table 4 it is seen that the shear lip of the drop-weight specimen decreases with decreasing temperature. For example, the drop-weight specimen of the TV alloy (13V-11Cr-4Al) exhibited a 0.05-in. shear lip when tested at 85 deg F; at 0 deg F no shear lip was measurable. For the present no significance will be attributed to the shear lip factor until further work with titanium alloys is performed.

CRACK-STARTER TEST

The crack-starter test defines the various fracture transitions for steel occurring over a temperature range. An arbitrary FTP of 0 deg F was selected for defining this fracture requirement. The steel classifications are being used temporarily for defining the fracture characteristics of titanium. Both the type of fracture and the related fracture transition for titanium are listed in Table 5. Temporarily these designations are put into four broad classifications:

Fracture Classification	Fracture Designation
Complete Refusal	FTP or greater
Limited Tearing	Greater than FTE but less than FTP
Complete Tearing	Less than FTE but greater than NDT
Flat Break	NDT or less

It is emphasized that the classification given for a particular test condition is not conclusive. A great many tests will have to be run to obtain a true normalization curve. The results of these tests are considered as guidelines.

The results of the explosion crack-starter tests are plotted as closed symbols on the Charpy V-notch curves of Figures 7 through 14. Photographic inserts of the test plates are included. In all cases except one, the brittle behavior as determined by the explosion crack-starter test corresponds to the drop-weight test. The drop-weight behavior of the exception, RG, is being reinvestigated.

Table 5 summarizes the test results of the explosion crack-starter tests. Reductions were measured approximately 1 in. apart across the deformed areas. The percent reductions in thickness determined by the Model Basin occasionally differ from those reported by the Naval Weapons Laboratory. Since the measurements taken by the Naval Weapons Laboratory were made in the field at the time of the test, it is believed that the Model Basin measurements which were made later under laboratory conditions are more accurate.

The TV, TX, and CV alloys, Figures 7 through 9, failed without exhibiting deformation when tested at ambient temperatures (80 deg F). These results show that the ambient temperature was below the NDT temperature.

The MD and MG alloys and the one TG plate submitted broke into a number of pieces at 0 deg F. However, plastic deformation was noticeable and measurable. Since the TG plate

TABLE 5

Summary of Results of Explosion Crack-Starter Tests

TMB Designation	Plate Number	Charge Weight lb	Standoff Distance in.	Test Temperature deg F	Depth of Bulge in.	NWL Percent Reduction in Thickness	TMB Percent Reduction in Thickness	Fracture Classification	Fracture Designation
TV	1	7	15	80	-	0	0	Flat Break	< NDT
TX	2	7	15	80	-	0	0	Flat Break	< NDT
CV	2	8	15	80	-	0	0	Flat Break	< NDT
CVH	1	7	15	80	-	0	0	Flat Break	< NDT
MD	1	7	15	90	-†	7.4	5.1	Limited Tearing	< FTP
	3	7	15	0	-	0		Complete Tearing	< FTE
MG	2	7	15	0	-†	7.9	1.3*	Complete Tearing	< FTE
	4	8	15	90	-†	6.1		Limited Tearing**	< FTP
TG	6	7	15	0	-	0	1.9*	Complete Tearing	< FTE
RG	1	7	15	-75	-	0	2.5*	Complete Tearing	< FTE
	3	7	15	0	2.25	4.8	4.4	Limited Tearing	< FTP
MQ	2	7	15	80	2.25	7.5	6.7	Complete Refusal	> FTP
	3	7	15	-110	1.75	1.4	4.0	Limited Tearing	< FTP
TA	1	4	18	0	1.375	0.82	1.9	Complete Refusal	> FTP
	2	4	18	-110	1.313	3.8	2.3	Complete Refusal	> FTP

* For comparative purposes; extent of fracture precludes exact values.

** Plate tore in half, but fractured surface indicates shear failure. Complete tearing attributed to explosive overloading.

† Bulge depth not taken due to segment torn out in bulged area or specimen was torn in half in bulged area.

was the only plate of this alloy submitted by this producer, no Charpy V-notch or drop-weight test could be made. In relating these fractures to the steel designations, these specimens at 0 deg F were at or slightly below their FTE temperature. In Figures 10 and 11, the MD and MG fractures at 0 deg F are designated as complete tearing.

The results of other plates of the MD and MG alloys at ambient temperatures are somewhat ambiguous. The MD alloy indicated limited tearing parallel to the direction of roll. However, a crack travels around a small portion of the deformed area of the plate. The MG alloy was the first plate to be tested, and an 8-lb charge was used. A number of cracks emanated from the notch, two of the cracks stopping at the edge of the bulged area. One crack tore the plate in half in the transverse direction of roll. There was some confusion, however, as to which was the direction of roll, and this complete crack may actually have been in the longitudinal direction. Since the fracture appearance of the two halves indicated a shear type of failure, it is believed that the 8-lb charge probably overloaded the plate and tore it in half. These two plates are classified with certain reservations as having failed by limited tearing; these results are interpreted for the testing temperature of 80 deg F as falling between the FTE and FTP range.

The RG alloy, which has a similar composition to the MG and TG alloys, exhibited limited tearing when tested at 0 deg F. At -75 deg F the plate broke into three pieces, each piece having deformed considerably. These fractures are designated as limited and complete tearing, respectively, on Figure 12. The 0 deg F test indicates that fracture occurred at a temperature which is slightly below the FTP. The test at -75 deg F showed that failure occurred at or slightly below the FTE temperature.

Of the high-strength alloys the MQ alloy (8Al-2Cb-1Ta) demonstrated the greatest resistance in the explosion crack-starter test. At ambient temperature, 80 deg F, the plate exhibited complete refusal to crack. At -110 deg F the plate exhibited slight tearing. It is considered for this alloy that -110 deg F is slightly below the FTP. These results are compared with the drop-weight and Charpy V-notch data on Figure 13.

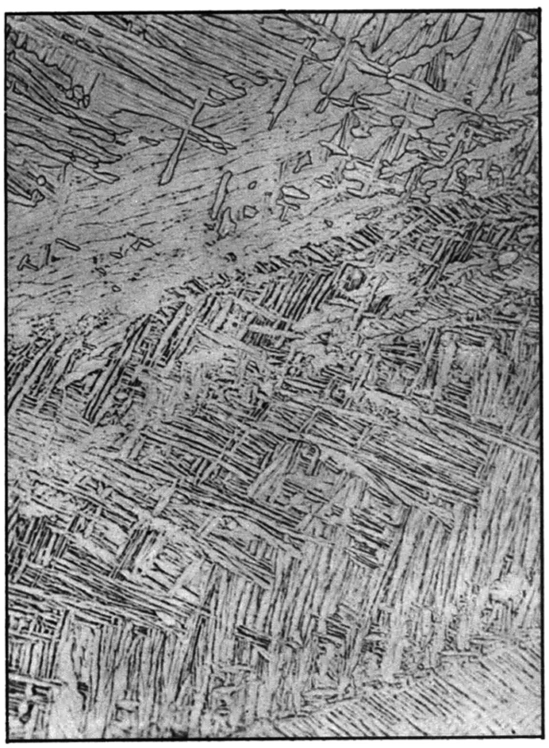
The unalloyed titanium, TA, was tested with a reduced charge of 4 lb, and the standoff distance was increased to 18 in. These changes in explosive charge conditions were believed necessary since its yield and tensile strengths were less than one-half those of the other alloys. Complete refusal to tearing was exhibited at 0 deg F and -110 deg F. Figure 14 demonstrates the comparative Charpy, drop-weight, and explosion crack-starter results. The reduction-in-thickness measurements indicate that the 4-lb charge at 18 in. was not a severe enough load, and that the material could have withstood a larger charge.

MACRO- AND MICRO-STRUCTURE

The broken Charpy V-notch impact specimens and drop-weight bars showed that all the titanium plates had different grain sizes. Macrograin sizes were measured on the majority of the alloys, and, wherever possible, compared with ASTM micrograin sizes. Finished grain size was measured for the TV, CV, CVH, and TX alloys. Apparent grain size was measured for the alloys exhibiting a Widmanstatten or basketweave structure, MD, MQ, RG, and MG alloys. The Widmanstatten structure is clearly outlined by the prior beta grain boundaries; see Figures 15 and 16. It was felt that this apparent grain size was the more realistic since these boundaries would contain the greater percentage of interstitial contaminates and thereby be the weakest zone under impact type of loading.

(TX) 6Al-4Zr-1V (400X)

Alpha



(MD) 5Al-2.5 Sn (80X)

(MQ) 8Al-2Cb-1Ta (80X)

Figure 15 - Photomicrographs of Alpha Titanium Alloys

(MG) 6Al-4V (200X)

Alpha-Beta

(RG) 6Al-4V (40X)

Alpha-Beta

Figure 16 - Photomicrographs of Alpha-Beta Titanium Alloys

Grain-size measurements are reported in Table 6. The TX alloy had the finest finished grain size of all the alloys, falling within the ASTM micrograin size 9. The MQ, MD, RG, and MG alloys revealed large apparent macrograins. The MQ alloy (8Al-2Cb-1Ta) exhibited the largest grain size of all the titanium alloys, apparent macrograin size M-6. The grains for this alloy were not equiaxed but resembled elongated rectangle

Photomicrographs of the principal titanium alloys are presented as Figures 15 through 17. Analysis of the structure is not made in this report, since interpretation of the microstructure of the titanium alloys depends heavily upon the prior processing history. For example, the MD and MQ photomicrograph in Figure 15 appear similar to MG and RG photomicrographs in Figure 16. The MD and MQ transformation is considered an acicular alpha structure. These alloys were probably heated above the beta transus in the rolling process, and the acicular alpha formed in the cooling sequence. The MG and RG alloy structures, Figure 16, could be acicular alpha, but, since the processing data are not available for evaluation and the constituents appear to have a microstructure similar to beta, the structure is classified as an alpha-beta structure. These tentative designations will be reevaluated upon receipt of processing data. The processing data and the microstructures of these alloys will be compared with the microstructures and resultant fracture transitions obtained from the studies on the effects of thermal treatments on notch toughness requested by the Bureau of Ships.[17]

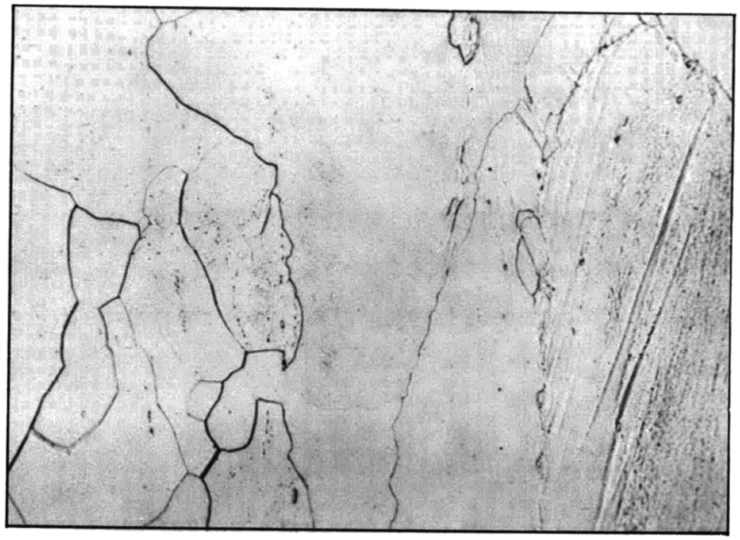
The microstructures of the all-alpha TX alloy, the beta TV and CV alloys, and the beta-aged CVH alloy will be discussed after a better understanding is obtained of the effect of small phase changes and interstitials upon notch toughness.

TABLE 6

ASTM Grain Size of Various Titanium Alloys

DTMB Designation	Composition	ASTM Macro-grain Size		ASTM Micro-grain Size		Nn[††]Nl[‡]	Comments
		Number	Method	Number	Method		
CV	13V-11Cr-4Al	M-11.5	Intercept*	ND[#]	-	1:1[‡‡]	Mixed grain size.
CVH	13V-11Cr-4Al	M12.5	Intercept*	00	Intercept*	1:1	Mixed grain size.
TV	13V-11Cr-4Al	ND[#]	-	3	Intercept*	2.4:1	
TX	6Al-4Z4-1V	ND	-	9	B&L Eyepiece[†]	1:1	
MD	5Al-2.5Sn	M-8.5[##]	Intercept*	ND	-	4:1	
MG	6Al-4V	M-15.5[##]	Intercept*	2	Intercept*	6.5:1	Severely deformed, grains not well defined.
RG	6Al-4V	M-10[##]	Intercept*	ND	-	1:1	
MQ	8Al-2Cb-1Ta	M-6[##]	Planimetric**	ND	-	10:1	

* Grain size determined using ASTM Intercept Procedure.
** Grain size determined using ASTM Planimetric Method.
† Grain size determined using B&L Grain Size Determination Eyepiece.
†† Nn = Average intercept distance normal to plate surface.
‡ Nl = Average intercept distance in longitudinal direction.
‡‡ The larger the grain size number the smaller the grain size. Equi-axed grains have a Nn:Nl ratio of 1:1.
\# ND = Not determined.
\## Apparent grain size.

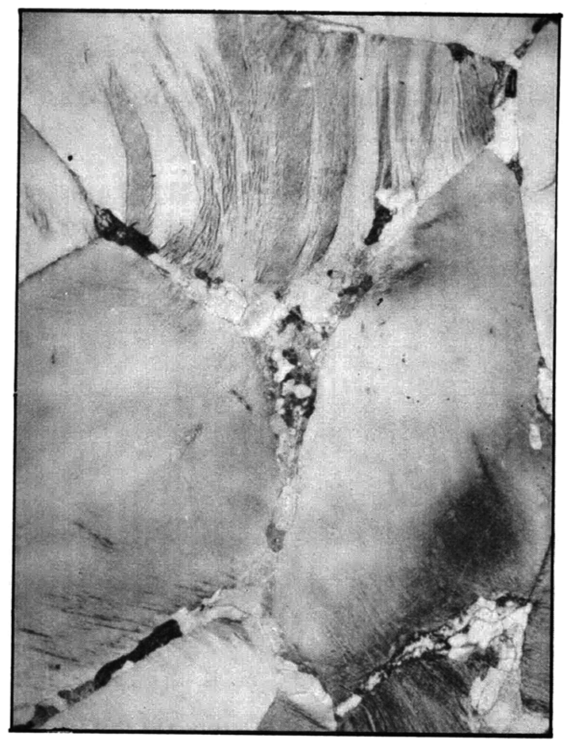


(TV) 13V-11Cr-4Al (200X)

Beta

(CV) 13V-11Cr-4Al (40X)

Beta



(CVH) 13V-11Cr-4Al (40X)
(Aged)

Beta-Alpha

Figure 17 - Photomicrographs of Beta Titanium Alloys

CREEP TEST

At present, one alloy, MQ (8Al-2Cb-1Ta), is being tested to evaluate its creep characteristics at room temperature. After 100 hr at a load equivalent to 0.8 of its yield strength, no creep tendencies were observed. Results of this test and of creep tests of other alloys will be reported in subsequent progress reports.

DISCUSSION

There was insufficient titanium material available for developing normalization test procedures for either the drop-weight or the explosion crack-starter tests. Therefore, the results of these tests can only be considered indicative rather than quantitative. Results for a given alloy phase, or even the same alloy made by two different manufacturers, for example MG and RG, Figures 11 and 12, are not comparable. This indicates that processing procedures used by the various manufacturers vary. The results on some of the alloys which failed to meet the NDT and FTP standards might meet or come near meeting these requirements by better control of the processing procedures.

The 0-deg-F FTP requirement is not considered severe because a military submarine must be able to withstand high deformations without tearing severely. If an operating temperature is above 0 deg F, localized fracture may occur in a deformed region in the presence of a notch. However, since the specified FTP temperature for a given alloy is 0 deg F, cracks will not propagate. These transition temperatures, FTP, 0 deg F, and NDT, -80 deg F, assure a safety factor under normal operating condition.

Although the investigation of the submitted unwelded alloy plates is not complete, the test results indicate that the titanium alloy 8Al-2Cb-1Ta in 1-in. plate can be considered as meeting all requirements for a submarine hull base material.

The unalloyed titanium, TA, met the requirements for fracture transition, but its low strength level eliminates it. A number of questions are still unanswered. First, can the results be reproduced? Second, will section thickness have an effect on the overall properties? Third, and most important, can the alloy be fabricated into shapes and welded?

The drop-weight and explosion crack-starter test results, which are compiled and superimposed on the Charpy V-notch curves of Figure 18, indicate that the temperature at which a complete flat break is obtained can be predicted by the Charpy V-notch curve. Titanium drop-weight or explosive crack-starter specimens will probably break at a temperature where the Charpy V-notch energies are below 21 ft-lb and have a corresponding lateral expansion of 10 mils or less. These levels should be considered only as a guide until more data are obtained on these and other alloys.

In the alpha and alpha-beta materials an unexpected and unexplained relationship is found in the apparent grain size. The larger the apparent grain, the greater resistance the material has to fracture. Table 7 correlates the drop-weight, explosion crack-starter, and Charpy V-notch data with finished and apparent grain size. For titanium alloys heated above the beta transus, apparent grain appears to be more indicative in correlating fracture transition than finished grain size.

Table 3 and Figure 5 indicate that the 8Al-2Cb-1Ta alloy (MQ) had the least sensitivity to rates of loading, whereas the 5Al-2.5Sn alloy (MD) had the greatest sensitivity. The 6Al-4V alloy, RG, had a rate sensitivity between these two. Since these alloys have essentially the same microstructure, acicular alpha, and their yield strengths were approximately the same for a very low rate of loading, the difference in rate sensitivity may be related to interstitials. There appears to be a relationship between rate sensitivity and

TABLE 7

Correlation of Grain Size, Charpy V-Notch, Drop Weight, and Explosion Crack-Starter Test Data

DTMB Designation	Alloy Composition	ASTM Macrograin Size	Test Temperature deg F	Charpy V-Notch Properties				Drop-Weight Test	Explosion Crack-Starter Test	
				Longitudinal		Transverse				
				Energy ft-lb	Lateral Expansion mils	Energy ft-lb	Lateral Expansion mils	Fracture†† Characteristic	Fracture Classification	Fracture Designation
TV	13V-11Cr-4Al	3*	80	11	4.5	12.5	7.5	Broke	Flat Break	< NDT
TX	6Al-4Zr-1V	9*	80	17	8.5	15.5	6	Broke	Flat Break	< NDT
CV	13V-11Cr-4Al	M-11.5	80	7.5	4.5	9.5	4.5	Broke	Flat Break	< NDT
CVH	13V-11Cr-4Al	M-12.5	80	-	-	-	-	Broke	Flat Break	< NDT
MG	6Al-4V	M-15.5‡	90	25	14	26	14.5	-	Limited Tearing**	< FTP
MG	6Al-4V	M-15.5‡	0	22.5	9.5	25	11	Limited Tearing	Complete Tearing	< FTE
MD	5Al-2.5Sn	M-8.5‡	90	29	21.5	32	21	Complete Refusal†	Limited Tearing	< FTP
MD	5Al-2.5Sn	M-8.5‡	0	25.5	16	27	15	Complete Refusal	Complete Tearing	< FTE
RG	6Al-4V	M-10	0	31.5	14.5	32	16	-	Limited Tearing	< FTP
RG	6Al-4V	M-10	-75	28.5	13	27.5	12	-	Complete Tearing	< FTE
MQ	8Al-2Cb-1Ta	M-6‡	80	39	27	44	26.5	-	Complete Refusal	> FTP
MQ	8Al-2Cb-1Ta	M-6‡	-110	25	14.5	24.5	12	Limited Tearing	Limited Tearing	< FTP

* ASTM micrograin size.

** Plate tore in half but fracture surface indicates shear failure, complete tearing attributed to explosive overloading.

† Drop-weight specimens tested at 0 deg F did not break.

†† This information, except for fractures having complete break, is for information purposes only.

‡ Apparent grain size.

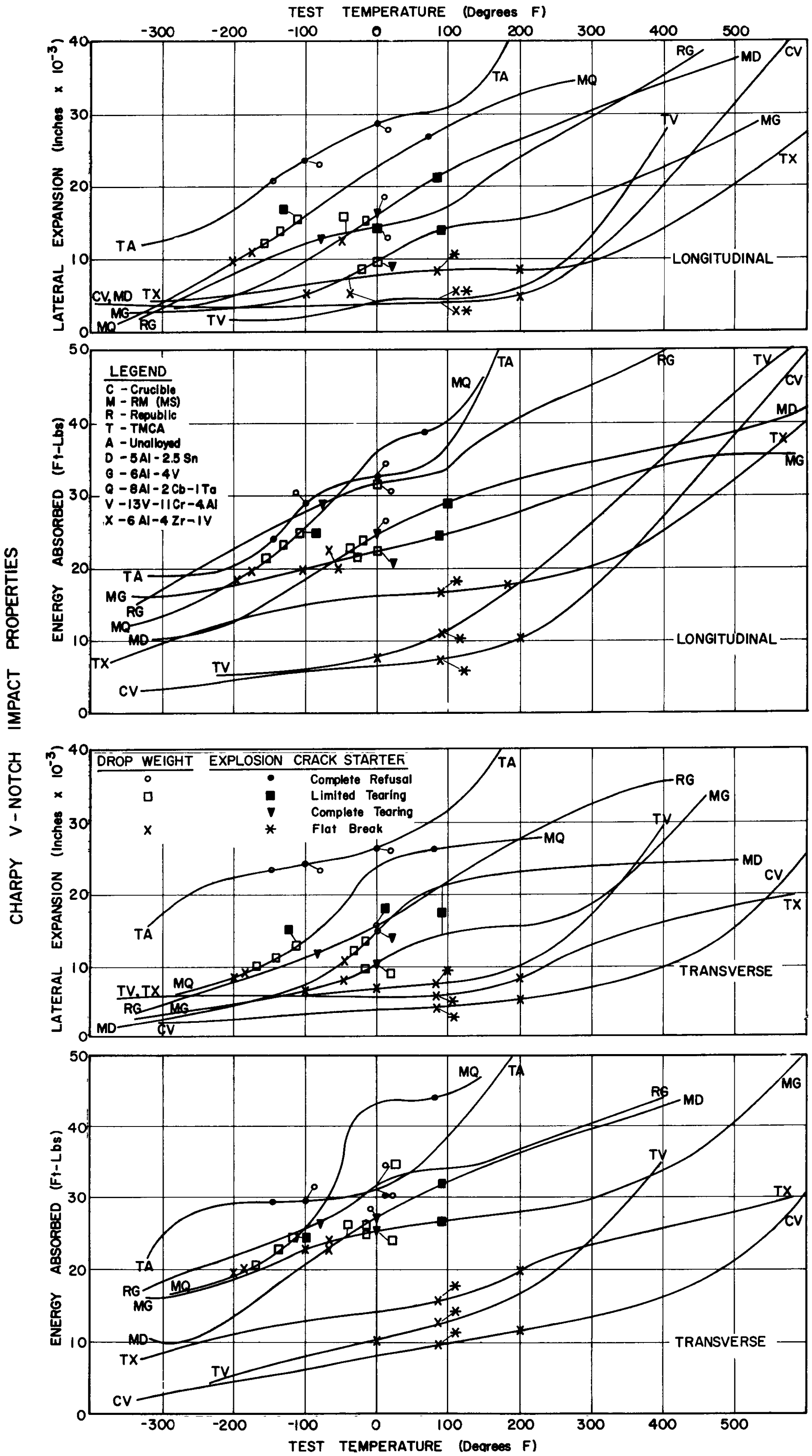


Figure 18 - Charpy V-Notch Curves with Comparative Drop-Weight and Explosion Crack-Starter Data of Various Titanium Alloys

fracture transition. The MQ alloy, having the least rate sensitivity, exhibited the greatest resistance to fracture. The RG which had an intermediate sensitivity to rate of loading was second best for fracture resistance.

The 8Al-2Cb-1Ta alloy, which nominally was to have a chemical composition corresponding to titanium alloy designation MSM-821, does not meet the nominal percent tantalum requirement. The producer reports a tantalum content of 2.07 percent rather than 1 percent. This may or may not be significant in the results obtained from the various tests, and it bears more investigation.

CONCLUSIONS

All the alloys tested met the minimum tensile property requirements. Only the MQ alloy met the fracture transition requirements. The RG alloy met the NDT temperature but failed to meet the FTP, whereas the same alloy, MG, manufactured by another producer, and other alloys failed to meet either NDT or FTP requirements. However, the results of these tests are not necessarily considered to be the optimum properties that can be obtained from these alloys since methods of processing and the presence of interstitial elements significantly affect the behavior of the material. With improved processing techniques it is believed that the other titanium alloys can be made suitable as a submarine hull material.

FUTURE WORK

In addition to the program now under way, it is planned to investigate the MSM 821 alloy and modifications thereof more completely as a material for deep-diving submarines. MSM-821 is the designation given by the manufacturer. The Model Basin designation for this alloy throughout this report is MQ.

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