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QUASI-STATIC COMPRESSION AND TENSILE STRESS-STRAIN CURVES, TANTALUM - 10% TUNGSTEN AND 300 GRADE MARAGING STEEL

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May 1986

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report presents the results of quasi-static compression and tension tests of tantalum -10% tungsten alloy and Vascomax 300 CVM 300 grade maraging steel. Young's modulus, Poisson's ratio, and yield strength and ultimate strength were determined at test temperatures of 23.9°C. Results provide engineering properties documentation for materials used in several terminal ballistic tests.

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I. INTRODUCTION

This report documents the results of quasi-static tensile and compression tests of a commerically available tantalum-10 percent tungsten alloy (Ta-10W) and a commercially available maraging steel. These two alloys were used in projectiles of a number of designs for laboratory ballistic tests. Experimentally determined Young's modulus, Poisson's ratio, yield and ultimate strengths, and engineering and true stress-true strain curves are presented. The tests were conducted for the Penetration Mechanics Branch (PMB), Terminal Ballistics Division (TBD), Ballistic Research Laboratory (BRL), by the Solid Mechanics Branch (SMB), TBD. This effort is part of SMB's Core Materials Program, and this report is one in a series of reports [references 1-8] characterizing the material properties of armor and penetrator materials. The data are useful for the design of projectiles, and the idealized stress-strain curves are used to improve the materials' characterization in existing and future finite element computer codes modeling the penetration process.

II. MATERIALS

The tantalum alloy was used alone in long rod penetrators for ordnance velocity phenomenology firings as a generic commercially available high density metal. It was investigated as a practical substitute for ballistic tungsten or uranium alloys. It was also used as a core material in two conceptual increased velocity projectiles designed to be launched from a weaponized light gas gun. The increased velocity projectiles had conical flight bodies. A thin skirt of 300 grade maraging steel with a central hub or sheath carried a tantalum alloy core. On the air defense version, firings were primarily conducted to determine values for aeroballistic coefficients, with proof-of-concept targets for terminal effects mounted at the end of the flight tunnel. The tantalum alloy was in the form of ballast slugs. On the anti-armor version, a tantalum-alloy rod formed a full-length penetrator along the central axis of the round.

Test specimens were machined from five tantalum bars. Material certifications were available for those from two lots, and are reported in Table 1. Work hardening is the only practical hardening mechanism for this alloy. The bar properties result from the amount of cold working following the last process anneal: the more reduction in area, the higher the yield strength and the lower the elongation to rupture [9]. Subsequent stress relief, recrystallization, or annealing causes reduction in yield and increase in elongation to rupture. Commercial practice is to supply Ta-10W bar either in the as-rolled (fully work hardened) or in the fully annealed condition, unless the purchaser makes special arrangements with the supplier. Therefore, the assumption is made that the uncertified bars are in one of these two conditions.

To check the microscopic structure of the material, longitudinal and transverse specimens of the annealed 3/8 inch (9.52 mm) diameter Teledyne Wah Chang bar used in test T152 were sectioned, polished, and etched five minutes in a solution made by mixing 30 millilitres each of concentrated hydroflouric acid, concentrated sulfuric acid, and water, to which five drops of an aqueous solution of 30 percent hydrogen peroxide was added. Representative micrographs are presented in Figures 1 and 2. In addition, 1000 gram Tukon micro-hardness measurements were made on the transverse section, yielding Knoop hardness

Table 1. Reported Ingot Analyses for Three Ta-10W Samples

Producer	Fansteel	Teledyne/Wah Chang Albany	
Bar Diameter	1/2 Inch	3/8-Inch	
Production Order No.	644-W31619-0	6827	
Heat/Lot No.	60B-3S32	620297 Ta-10W	
Certificate Date	10 Dec 75	5 May 76	
Ingot Brinell		High 197	
Hardness Number		Average 194	
3Kg Load		Low 189	
Sample Location	Unspecified	Top	Bottom
	Composition		
Alloying Elements			
Ta	Balance	Balance	Balance
W	9.48%	10.1%	10.3%
Impurities (PPM)			
H	<5	<5	<5
C	<10	<30	<30
N	12	<5	7
O	41	<50	60
Si		<40	<40
Ti	<20		
V	<20	<20	<20
Cr	<10	<20	<20
Fe	<20	<40	<40
Co	<20	<10	<10
Ni	<20	<20	<20
Cu		<40	<40
Zr	<20		
Cb(Nb)	650	<20	<20
Mo	<20	<20	<20

Notes:

1. The bar chemistry can be expected to be higher in hydrogen, nitrogen, oxygen, and possibly carbon by virtue of the metal's affinity for, and its exposure to, these elements during processing from the ingot into the bar product.

2. Data are from certificates accompanying the material.

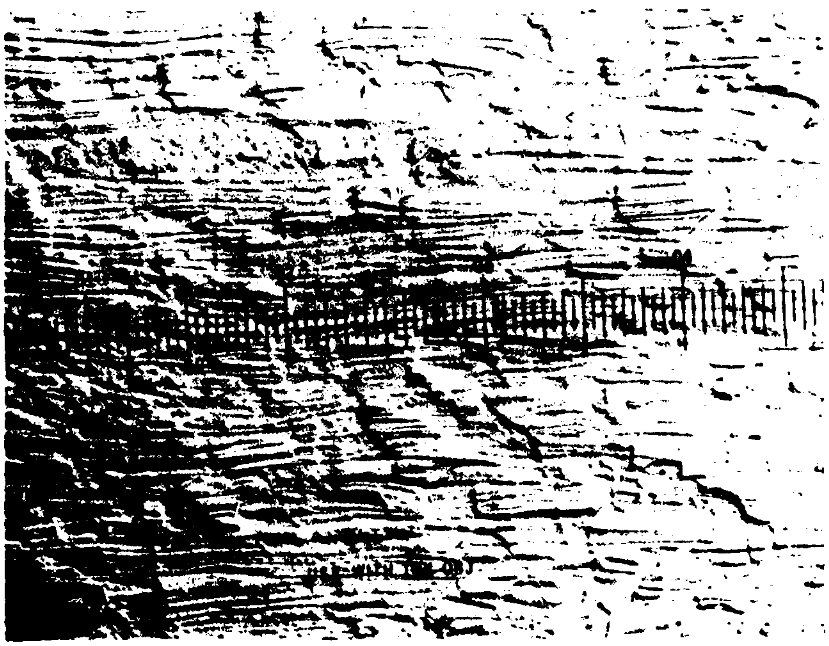

Figure 1. Longitudinal Sections of Annealed Ta-10W Bar. Bar was used on tensile test T152. Top photo is from edge and bottom photo is from middle of bar. Reticle is graduated in inches.

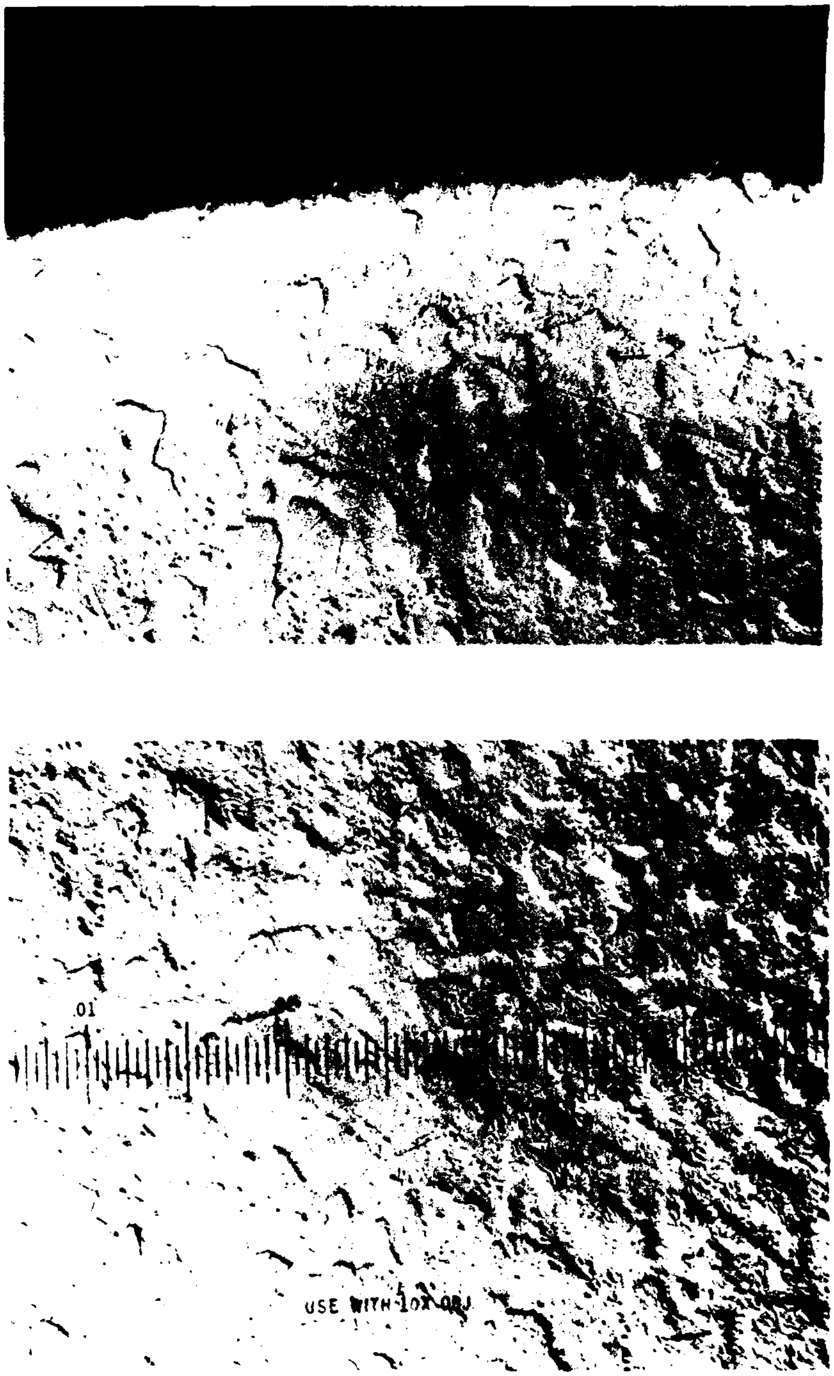

Figure 2. Transverse Sections of Annealed Ta-10W Bar. Bar was used on tensile test T152. Top photo is at the edge of the bar and bottom photo is from the middle of the bar. Specimen is overetched. Reticle is graduated in inches.

numbers. There was no significant difference in hardness with position in the section. The average hardness (total of 20 impressions) was 227.7 Knoop. It seems as if every hardness measurement reported in the literature is based on a different scale. To provide some feeling for the relationship between hardnesses on several commonly used scales, Table 2 is presented. It was prepared from relevant portions of two tables in reference 10 for nickel alloys. We believe these to be the best figures readily available with which to compare the hardnesses of tantalum alloys. It should be remembered that the hardness measured is a function of the indenter and sample geometry, the applied load, and the material indented, so values will be approximate.

Table 2. Hardness Conversions for Nickel Alloys
(From Reference 10)

Knoop 1000 g Knoop Indenter	Vickers 10 kg Vickers Indenter	Rockwell B 100 kg 1.588 mm Ball	Rockwell C 150 kg Diamond Indenter	Brinell 3000 kg 10 mm Standard Ball
204	179	88	<6.5>	176
215	188	90	<9.0>	184
226	198	92	<12.0>	194
239	209	94	<14.5>	204
251	220	96	<17.0>	215
267	234	98	20.0	228
283	248	100	22.5	241
304	266	<102>	25.5	258

Note: Values in brackets fall outside recommended ranges of applicability.

The 300 maraging steel tested is without certification. The specimens are from the same bar from which the projectiles were fabricated. The test results support a conclusion that the material is indeed a 300 maraging steel. The hardening process in maraging steels is to solution anneal the material by heating to 820 ^{o}C to convert the structure to austenite and then to air cool thru an M_f of 1000 ^{o}C, at which essentially all of the structure has finished its transformation back to martensite. Reheating to 480 ^{o}C and holding for six hours strengthens the material by precipitation and an order-disorder reaction. Considerable variation in temperature and time at temperature will not seriously affect the material properties. Although there is some variation in properties with rolling direction, the only practical way to significantly change the yield strength is to change the composition. Hence, the yield strength when hard indicates which grade of maraging steel is being used. In this case, the average yield strength of 2079 plus or minus 76 MPa is essentially indistinguishable from the typical value of 1996 MPa for a 300 maraging steel given in reference 11, versus the typical value of 1750 MPa cited for 250 maraging steel, the next closest grade.

III. TEST PROCEDURES

The testing apparatus, procedures, and data reduction regimen have been reported previously in references 1, 2, 6, and 7, and are in general accord with the ANS standards [13, 14]. The test specimen geometries, however, are quite variable. The specimens in general must be prepared from available material, which is frequently too short and too small in diameter to prepare standard specimens. The limited number of grips which we have for our testing machine likewise constrains overall specimen geometry. Because the elongation to rupture is sensitive both to the processing history of the bar from which the sample is taken, and to the specimen size, it is desirable to select a single standard specimen diameter so as to measure the former value without the influence of variations in the latter. With the exception of two tensile specimens (T152 and T153) for which the nominal reduced section diameter was 5.05 mm, this was accomplished using a 1/4 inch (6.35 mm) nominal reduced section diameter. The compression specimens were likewise nominally 1/4 inch diameter and 3/4 inch long (19.05 mm). All of the specimens were machined with the final cut being no deeper than 0.13 mm and the circumferential tool marks were removed by polishing with emery paper followed by crocus cloth. The surface finish was 0.8 micrometre RMS or less, with the lay about 45 degrees in both directions to the specimen axes.

The stress for each specimen was measured by recording the output of a load cell. All the specimens except the one used for the grip test (discussed later) were instrumented with adhesive bonded (M-Bond 200) foil resistance strain gages (BLH type FAET 06D-12 PEL). The strain was not expected to exceed 10 percent, so that no other strain measuring technique was used on the initial Ta-10W tensile test, T107. The tantalum alloy proved to be considerably more ductile than that, so that the strain record is incomplete on this specimen. Following that, an assortment of strain measuring techniques was used. Because the size of the material available for testing was frequently minimal, the specimens were frequently shorter than desirable. Where the reduced section length and end geometry permitted, a one inch extensometer was the preferred strain measuring means. Otherwise, the gage marks were scribed on the tensile specimens and were periodically photographed during the progress of the test. On the 5.05 mm diameter reduced section specimens, a one-half inch extensometer was used in addition to photographing scribed gage marks. The gage marks were frequently spaced less than four specimen diameters apart, so that the tensile strain data had to be corrected to a standard gage spacing before being further reduced. Tensile tests were continued to specimen fracture, while compression tests were terminated at gage failure or extensive specimen bending. The hardness of most of the specimens was measured. Where the impression was made on a cylindrical surface, the hardness was corrected to that which would have been measured on a flat surface, in accordance with USA Standard Z115.6-1967 [15]. All of the tests were performed at a constant 23.9 degrees Celsius, while the relative humidity varied from 33 to 49 percent. A summary of the pertinent experimental parameters is presented in Table 3.

Table 3. Experimental Parameters

Material	Bar Dia. (inch)	Source[a]	Test Type & No.[b]	Additional Instrumentation[c]	Hardness[d] (HRC)	Sample or Gage Length (mm)	Sample or Reduced Diameter (mm)
Tantalum - 10% Tungsten, All Specimens Axial	3/8	NSWC	C104	None	20	19.08	6.39
	3/8	NSWC	C105	None	20	17.32	6.35
	3/8	NSWC	C106	None	20	19.08	6.39
	1/2	NSWC	T107	None		No Marks	6.36
	1/2	NSWC	T108	Photo		7.06	6.22
	3/8	NSWC	T109	Photo	20	4.18	6.31
	1/2	AEDC	T110	1" Ext.	HRB 101	No Marks	6.32
	3/8	TWCA	T152	Photo and 1/2" Ext.	HRB 92	20.14	5.05
	3/8	TWCA	T153	Photo and 1/2" Ext.	23	20.34	5.07
	1/4	FMGT	T200	1" Ext.	23	Many @ 5.08	6.30
300 Maraging Steel (Vascomax 300 CVM), 1 3/8" Dia. Bar End Marked 52 3461A, Axial		NSWC	C111	None	51	19.04	6.36
		NSWC	C112	None		19.05	6.35
		NSWC	C113	None	52	19.02	6.39
		NSWC	T114	Photo		6.74	6.35
		NSWC	T115	Photo	51	7.30	6.34
Transverse		NSWC	C116	None	52	19.05	6.37
		NSWC	C117	None	52	19.06	6.29

Notes:

a. NSWC -- Naval Surface Weapons Center, White Oak, MD.
TWCA -- Teledyne Wah Chang Albany.
AEDC -- Arnold Engineering Development Center, Arnold AF Station, TN.
FMGT -- Fansteel Metals. SMB tensile test grip test.

b. T indicates tensile, C indicates compression test.

c. All samples were strain gaged except T200. Photo indicates photographic coverage of scribed gage marks, 1/2" or 1" Ext. indicates extensometer.

d. HRB and HRC -- Hardness on the Rockwell B and C scales.

IV. GRIP TESTS

The Ta-10W bar used for long rod penetrator phenomenology firings was 6.86 mm (.270 inch) diameter. For material properties tests, it was desirable to maintain the 6.35 mm reduced section diameter used in the bulk of the other tests. Mr. Victor Bates, Division Technical Manager, Fansteel Metals (a producer and potential supplier) suggested we use the technique that they use to obtain properties of full size bar. They use a 250 mm specimen length, reduce the diameter at the center about five hundredths of a millimetre, (0.002") using abrasive paper, mark the bar with fiducial marks every bar diameter, and pull the specimen to failure using checkered vee grips. SMB, TBD, did not have grips of precisely the design suggested, so it was not clear if the available grips would adequately hold the specimen without it pulling out. The alternative would be to use a 5.05 mm diameter reduced section specimen, with either 1/4-28 UNF or 1/4-32 UNEF threads on the end, but this was less desirable because the reduced size increases the experimental difficulties and the cost. In this case, this procedure also requires removing material in the specimen that is present in the real item, making the sample less representative. Mr. Bates kindly supplied us gratis with two 125 mm long specimens of fully work-hardened 6.35 mm diameter Ta-10W bar to investigate the various gripping methods. The use of checkered grips proved successful. While not the original goal of the testing, we were partially successful at obtaining additional stress-strain histories.

The material supplied was visually inspected and appears to be as-rolled material cleaned by etching, based on the frosted appearance and on seeing what must be flow lines -- wavy longitudinal striations not normally present on machined or abrasive finished material. The specimens were slightly out of round, running from 6.312 mm to 6.350 mm diameter. One end of one piece had a 0.08 mm deep gouge in it, so it was set aside for use as a threaded-end specimen if needed. Hardness was measured on freshly sanded ends on both specimens, and averaged HRC (Hardness on the Rockwell C scale) 23.0 with a standard deviation of 1.83. The reduced section diameter was produced on the grip test specimen by chucking it in a lathe and using #240 and then #320 grit 3M Tri-M-ite WETORDRY trademark silicon carbide paper, wet with a trichloroethane base coolant, to remove about 0.05 mm in the center. An 0.1 micrometre RMS finish was produced, with the lay circumferential. Two stripes with the same surface roughness but with the lay parallel to the long axis of the specimen were then created on diametrally opposite sides with #320 grit paper to provide contrast when scribed. Pairs of light transverse grooves were scribed on the specimen at nominal 0.200 inch intervals (5.08 mm), starting at an arbitrary location. The position of these marks was then measured with the same travelling microscope used to measure deformed length. Three diameters were measured and averaged at each gage mark to permit the computation of diametral strain.

The specimen was mounted in the Instron tensile test machine with the gage mark stripes oriented so as to be unmarred by the grips, with approximately 25 mm of material in each grip. This left approximately 6 mm of grip insert overhanging, which, combined with the tapering of the end grooves, formed a transition from full embossing of the specimen at its ends to just lightly embossing it at the grip ends. The grips were of a vee wedge design with 1 mm pitch transverse grooved surfaces on each of the two vee faces of the insert. The grooves were similar to sharp crested buttress threads. The inserts bore no trade name, but were supplied with the testing machine and had "S-25" on the hidden end, and ".280-.500" on the other. Two layers of 3M Tri-M-ite WETORDRY trademark silicon carbide paper were wrapped on the zero end of the specimen. A one-inch clip extensometer was mounted on the specimen centered at 62 mm (2.45 inches) from the zero end and was connected to a chart recorder.

The test was run with the heads separating at 0.5 mm/min. The chart record was watched for evidence of slippage in the grips, but none was found, with the test terminating on specimen rupture. Figure 3 presents photographs of the two gripped ends of the specimens.

Necking occurred inside and very close to one extensometer knife edge. When the chart indicated a leveling out of load at near the expected yield, it was first interpreted as slippage in the grips, and the onset of necking was not noticed until it had obliterated a fiducial line. Thus, it was not possible to deduce whether the scribe mark initiated the necking. The test proceeded until the specimen broke. The break was nominally a cup and cone fracture, but was very unusual in that it was very clearly square. Possibly the change in lay of the surface finish around the circumference may have contributed to this, but close inspection of the ends suggest that this was almost certainly not the case. Since the processing history of the bar is unknown, additional speculation is fruitless. Figure 4 shows the broken specimen, and a close-up of the fractured ends.

The scribe marks were purposely closely spaced to provide detailed data about necking and incipient necking. The specimen was reduced by 1.5 percent of initial diameter at the smallest section. The ASTM standard test method recommends 1 percent, and this still was not adequate to precipitate necking there. The original profiles, radial strain, axial strain with the 0.2 inch and 1 inch gage lengths, initial and final areas, and per cent reduction in area are plotted in Figure 5. Note an incipient neck at about 20 mm from the zero end, indicated most clearly on the radial strain plot. Due to the lack of strain gage data, the elastic modulus and Poissons's ratio were not obtained. With necking occurring at one leg of the extensometer, detailed stress-strain data were likewise lost. However, the yield and ultimate strengths on this test were used in calculating the average values.

V. DATA REDUCTION PROCEDURES

The ASTM standard for tensile specimens sets the gage length at four times the diameter of the specimen. The distances between fiducial marks used in the photographic strain measuring technique were not in accord with this in most of these tests. Therefore, it was necessary to develop an expression that can infer what strains would have been measured had the proper gage length been used. Such an expression is developed below, based on the assumption that after the specimen has reached its ultimate strength the only elongation taking place will be between the two fiducial marks.

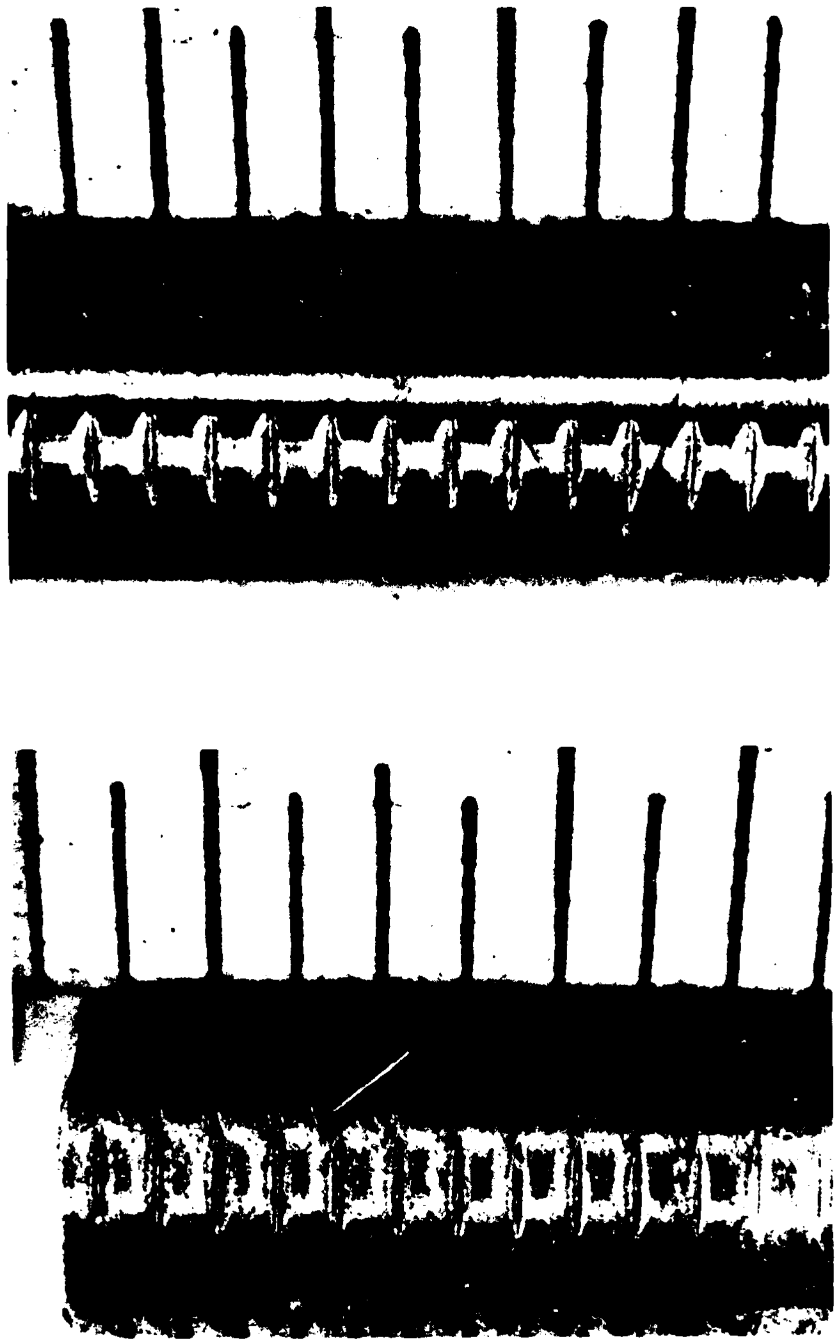

Figure 3. Embossing of 1/4 Inch Diameter Work-hardened Ta-10W Bar Specimen by Serrated Grips (Test T200). End in lower picture was wrapped with abrasive paper, while that in upper picture was bare. Scale graduations are 1/16".

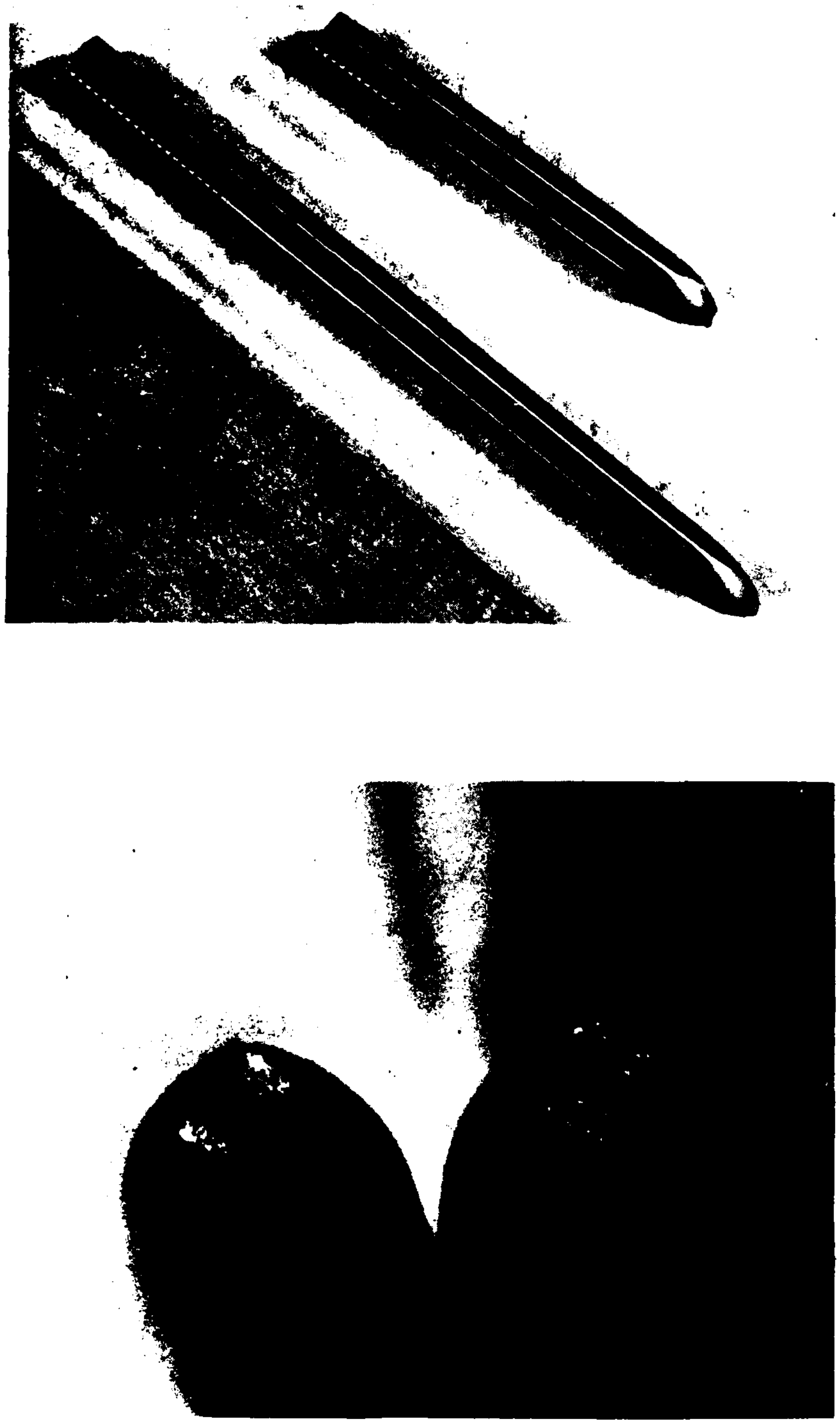

Figure 4. Fractured Fully Work-hardened Ta-10W Grip Test Specimen (Test T200). Scale in upper photo graduated in inches and sixteenths. Lower photo shows unusual square break.

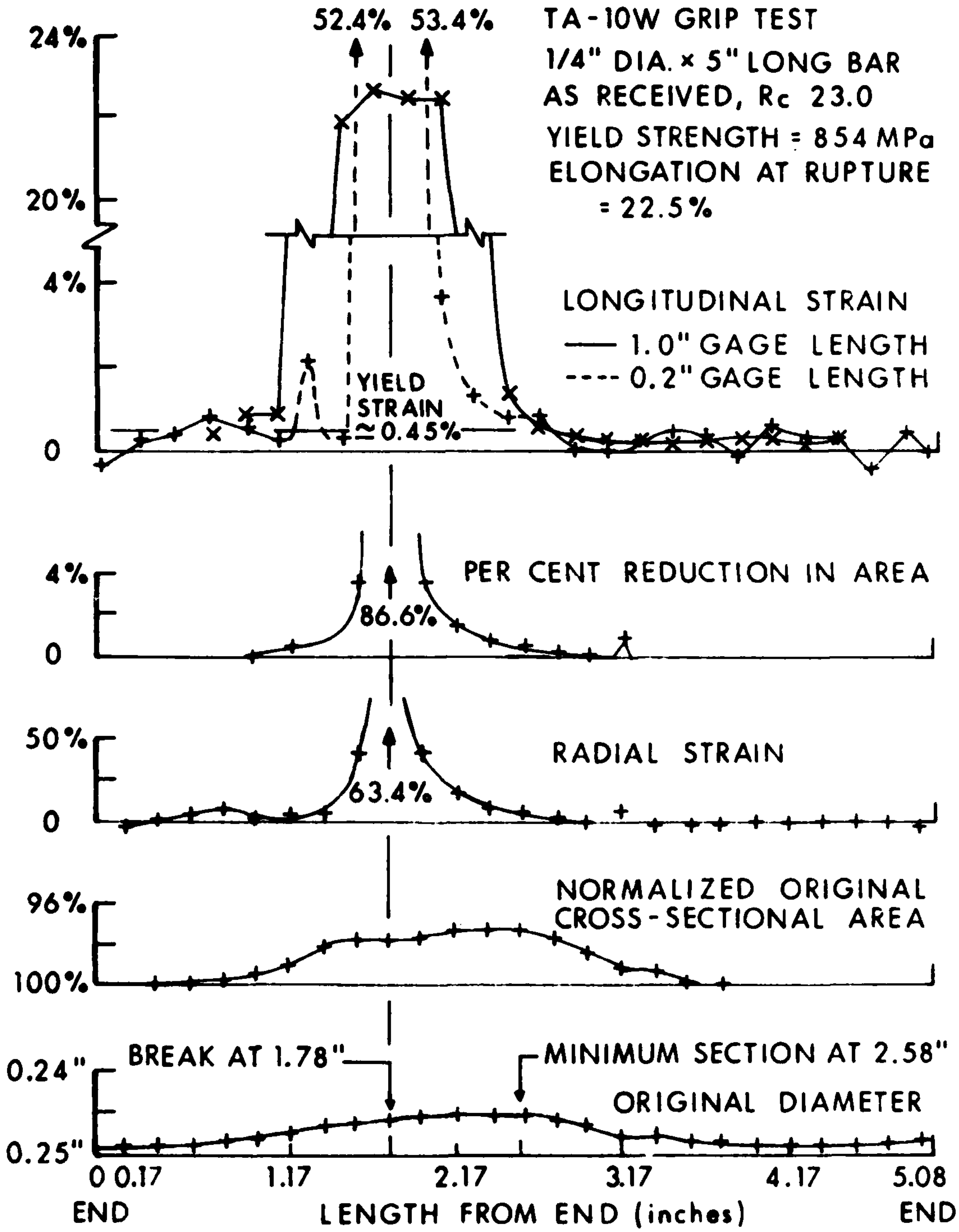

Figure 5. Data Plots from Grip Test of Fully Work-hardened Ta-10W Specimen (Test T200).

Given:

Lo = initial gage length between fiducial marks used in the experiment, and

L'_o = any other initial gage length for which an equivalent strain is sought.

Let $K = \frac{L'_o}{L_o}$.

Until necking occurs the strain is assumed to be uniform along the sample and is given by:

$$\epsilon = \epsilon' = \frac{L_o + \Delta L_o - L_o}{L_o} = \frac{\Delta L_o}{L_o} , \qquad (1)$$

where ϵ = engineering strain as measured between the gage marks used,

ϵ' = engineering strain which would be measured between marks separated by gage length L'_o, and

ΔL_o = increase in length between fiducial marks used.

At the ultimate stress, define

$$\Delta L_u = \Delta L_o.$$

Beyond this point, necking is assumed to begin. Calling unit elongation at a point the strain, and the average unit elongation between gage marks the unit elongation, the strain and the unit elongation are no longer identical. There is very high strain in the necking area and little additional strain in the unnecked areas between the gage marks. Thus, different gage lengths result in different reported elongations. The unit elongation as seen by the fiducial marks would be equal to

$$\epsilon = \frac{\Delta L_u + \Delta L_n}{L_o} , \qquad (2)$$

where L_n is the increase in distance between fiducial marks experienced during necking.

The equivalent unit elongation for marks initially separated by L'_o would be:

$$\epsilon' = \frac{\Delta L'_u + \Delta L_n}{L'_o} = \frac{K\Delta L_u + \Delta L_n}{KL_o} . \qquad (3)$$

Solving for ΔL_n from Equation 2 and substituting it into Equation 3, one obtains:

$$\epsilon' = \frac{K-1}{K}\frac{\Delta L_u}{Lo} + \frac{\epsilon}{K}. \quad (4)$$

Therefore, by measuring the unit elongation between existing gage marks at the ultimate stress, one can infer the elongation that would be experienced between gage marks of a different spacing. Expression 4 was used to reduce the data from all tensile tests except T110 and T200 to a form consistent with values produced by tests using ASTM method E8-69 (ANS Z165.13-1971 [13]).

For the purposes of idealizing the stress-strain curves, a secant modulus was extracted from the data by averaging all the Young's moduli in each experimental run which were in a zone of mixed results. The beginning of this zone was selected as the first Young's modulus indicating full take-up on the tensile test machine. For strains up to about one half of the yield point, the moduli fluctuated from point to point, then began monotonically decreasing. The end of the zone was taken as the last modulus which was higher than its neighboring values. Each of these moduli were then averaged for each material in both tension and compression and this average modulus used for the Young's modulus in the idealized curves.

VI. RESULTS

The material properties are listed in Table 4. The yield strength is defined as that stress at which the specimens deviated 0.2 percent from proportionality of stress to strain. Young's modulus, yield strength and Poisson's ratio are determined from study of the foil strain gage records. The measured strains at rupture reported in Table 4 are in accordance with, or have been corrected by Expression 4 to that which would have been measured had the test been conducted in accordance with ASTM E8-69 [13]. There were no gage lines scribed on specimen T107, and therefore the strain at rupture was not measured. If the strain had been measured, it would have provided a comparison to that of T108, an identical specimen.

To estimate the strain at rupture for T107, the lengths of the post-test reduced sections of T107 and T108 were measured. Final strains were then calculated based on the changes in lengths of the reduced sections. The results for both tests were similar. Hence, it was assumed that the length of the reduced section at ultimate load for T107 would be approximated by that of T108, permitting expression (4) to be used to estimate the load at rupture for a standard gage length. For this calculation,

$$K = \frac{25.4 \text{ mm}}{38.1 \text{ mm}}, \qquad \Delta L_u = 7.62 \text{ mm}, \qquad \text{and} \qquad \epsilon = 27.6\%,$$

with the result that the final strain at rupture for T107 would be 31.4%.

The tantalum alloy specimens were extremely ductile and exhibited considerable plastic work outside the four diameter zone in which necking is presumed to occur, which violates the assumptions used to derive Expression 4. Hence, the estimates of stain at rupture for this tantalum alloy obtained from the overall length of the reduced section are less believable than those estimated from gage marks. Comparing strains estimated in this fashion with those corrected from non-standard gage marks provides a check on Expression 4. The details of the corrections to strain at rupture are reported in Table 5. The stess and strain data from photographic or extensometer records for tests T108 thru T110 and T114 and T115 are presented in Appendix Tables A1 and A2.

Table 4. Measured Material Properties

Material		Test Number	Young's Modulus (GPa)	Yield Strength (MPa)	Ultimate Strength (MPa)	Poisson's Ratio	Strain at Rupture (Percent)
Tantalum - 10% Tungsten	Fully Annealed	C104	Results discarded -- excessive specimen bending				
		C105	198.20	460		.316	
		C106	197.04	462		.320	
		T107	192.31	450		.318	31.0 [a]
		T108	193.55	475	578	.322	35.9 [b]
		T109	191.69	462	569	.321	19.9 [b]
		T152	191.39	440	547	.330	41.2 [c]
	Fully Work Hardened	T110	188.68	855	856	.331	20.6
		T153	202.53	824	870	.328	16.6 c
		T200		854	859		22.5
300 Maraging Steel	Solution Heat Treated	C111	199.14	2100		.300	
		C112	199.11	2100		.296	
		C113	200.44	2078		.298	
		T114	188.37	1977	2021	.310	12.0 [b]
		T115	187.83	1980	2023	.305	8.0 [b]
		C116	194.00	2160		.296	
		C117	186.67	2160		.288	

Notes:

a. Inferred from post-test examination.

b. Inferred from data from tests with non-standard gage lengths.

c. Average of photo and 1/2 inch extensometer corrected to 1 inch.

Table 5. Measured (Photographic) and Corrected Engineering Strain at Rupture

Material	Test	Initial Gage Length	Initial Reduced Section Length	Gage or R S Length at Max Load (Ultimate)	Final or R S Gage Length	Engineeering Strain at Ultimate Strength	Uncorrected Engineering Strain at Rupture	Engineering Strain at Rupture Inferred from Expression 4
		(mm)	(mm)	(mm)	(mm)	(percent)	(percent)	(percent)
Ta-10W	T107		38.10		48.62	20.0	27.6	31.4
Ta-10W	T108	7.06		8.48	12.50	20.0	77.0	35.9
			38.10	45.72	48.15	20.0	26.3	29.5
Ta-10W	T109	4.18		4.86	5.791	16.3	38.7	19.9
300M	T114	6.74		7.01	9.07	3.9	34.5	12.0
300M	T115	7.30		7.41	9.64	1.5	32.0	8.0

There were two classes of Ta-10W materials tested: fully annealed and fully work hardened. For the fully annealed material, Figure 6 presents engineering stress versus engineering strain in tension, to rupture, as measured via the photographic technique and calculated using expression (4), for tests T108 and T109. Note the extreme variation in elongation to rupture between the two samples. A stress-strain curve for the average of tests T107 thru T109, out to 7 percent strain, as measured by foil resistance strain gages, is presented in Figure 7. The error bands indicate plus and minus one standard deviation in the stress. Figure 8 presents engineering stress versus engineering strain for annealed Ta-10W in compression for test C105. The corresponding curve for a duplicate test, C106, deviated from that of C105 by less than 0.1 percent. For the fully work hardened material, Figure 9 presents an engineering stress versus engineering strain curve in tension, to rupture, for test T110.

For the maraging steel, Figure 10 presents a plot of engineering stress versus engineering strain, while Figure 11 replots the data as true stress versus true strain. The data are from test T115, with the strain measured from the photographic record and corrected as if the proper gage length had been used. True stress is defined as the intensity of load per unit of actual area, and is given by reference 16 as:

$$\epsilon_x = 2 \ln \frac{D_o}{D_f} ,$$

where D_o is the original and D_f is the final diameter, as determined photographically. Test T114 was a duplicate of T115, and the resulting curves are essentially identical. Figure 12 is the plot of the average engineering stress versus engineering strain for maraging steel in compression. Again, the error bands are at plus and minus one standard deviation. Figures 13 and 14 are photographs of the fractured specimens from all of the tensile tests except the grip test, T200, (shown earlier in Figure 4). Note that the ductility of the tantalum alloy is so extreme that it appears impossible to determine which specimens were fully work hardened and which were fully annealed from looking at the fractured tensile specimens.

The tantalum proved much more ductile than originally expected, and did not mimic the ballistic behavior of tungsten and uranium alloys. Increasing the reduction in area during the final rolling decreased the ratio of yield to ultimate strengths without significantly decreasing the ductility. The unexpectedly high ductility was attributed to the cleanliness of the product resulting from vacuum electric melting. The only viable approach to reducing the elongation appeared to be intentionally adding back embrittling agents in custom production, so further efforts at modifying properties were abandoned.

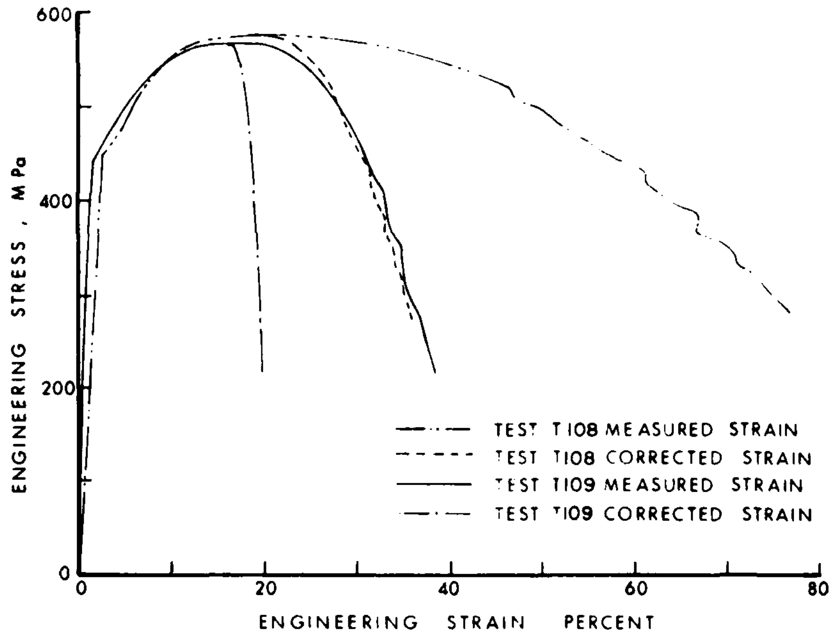

Figure 6. Individual Measured and Corrected Engineering Stress versus Engineering Strain Curves, to Rupture, for Annealed Ta-10W in Tension, from Tests T108 and T109.

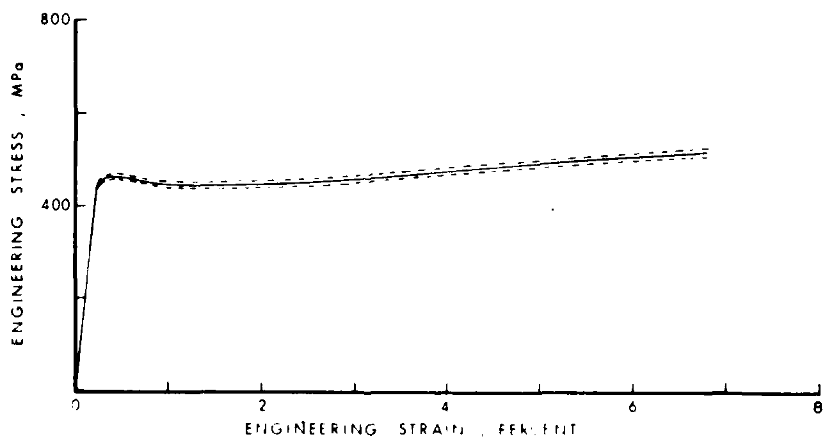

Figure 7. Average Engineering Stress versus Engineering Strain, to 7% Strain, for Annealed Ta-10W in Tension, Tests T107 thru T109.

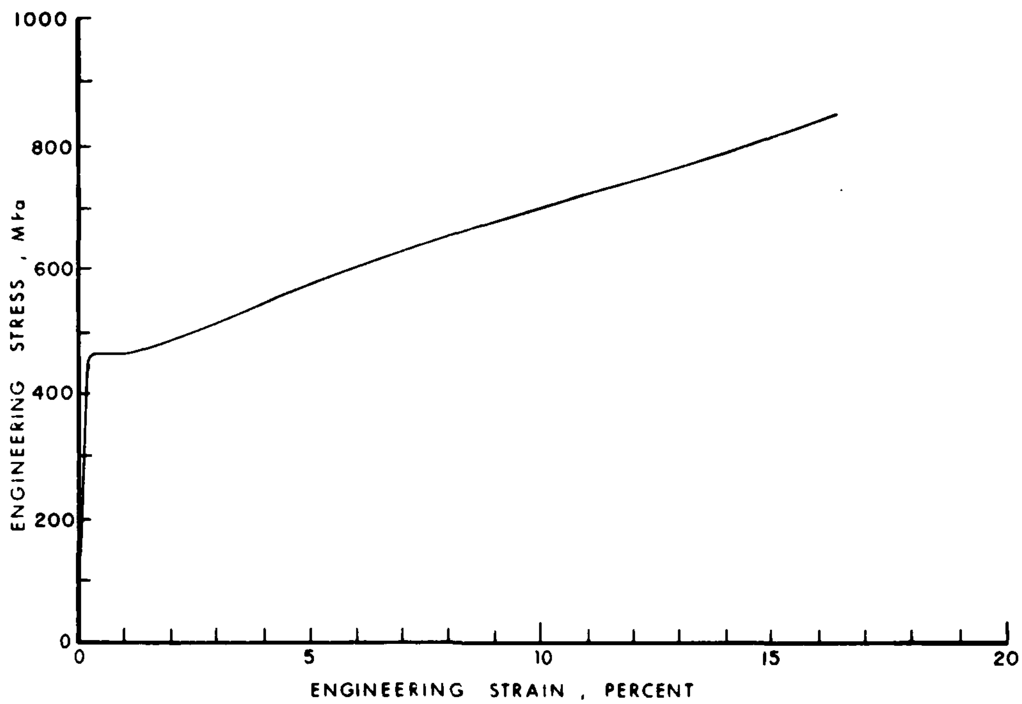

Figure 8. Engineering Stress versus Engineering Strain for Annealed Ta-10W in Compression from Test C105. The data from compression test C106 deviated less than 1/2% from this curve.

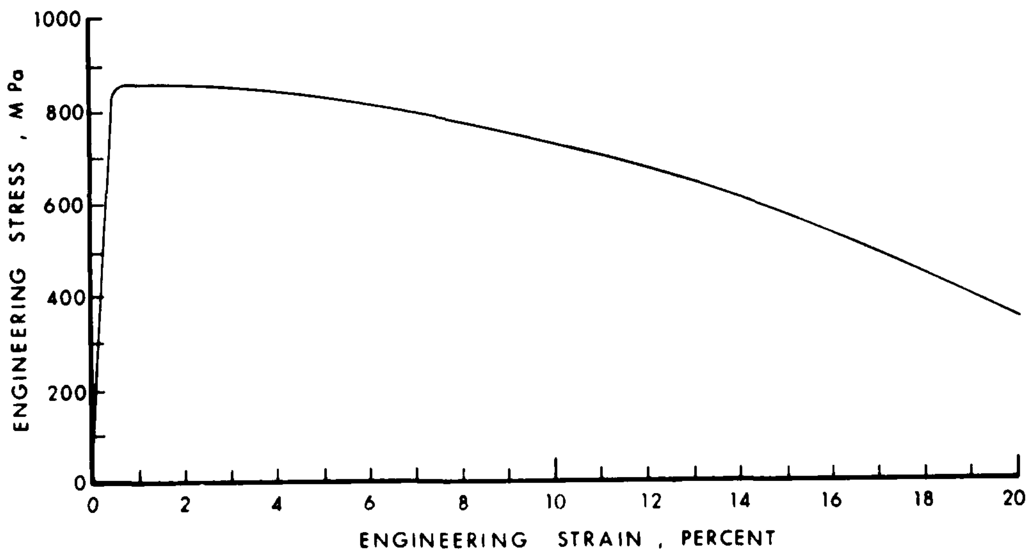

Figure 9. Engineering Stress versus Engineering Strain, to Rupture, for Fully Work-hardened Ta-10W in Tension, from Test T110.

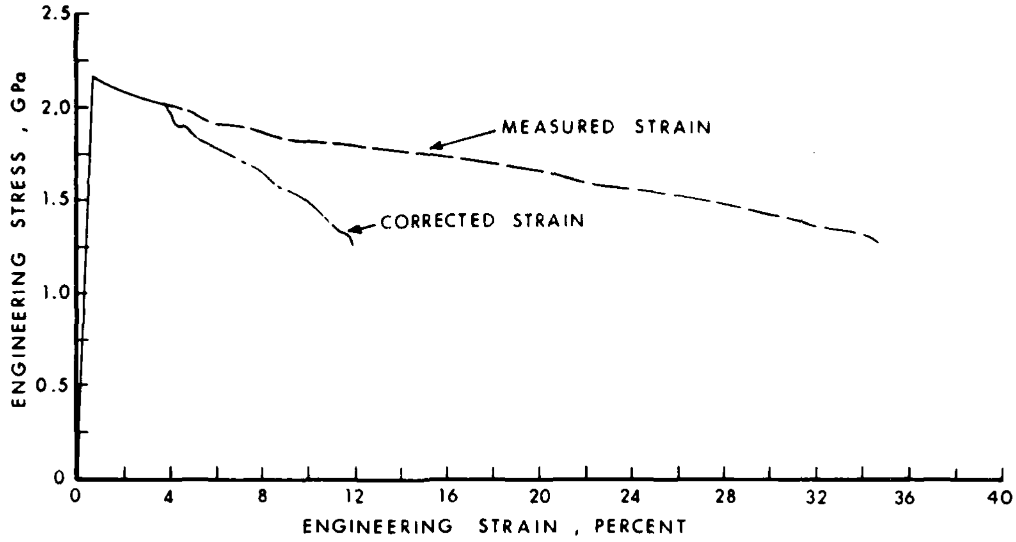

Figure 10. Measured and Corrected Engineering Stress versus Engineering Strain, to Rupture, for Precipitation Hardened 300 Maraging Steel in Tension, from Test T115.

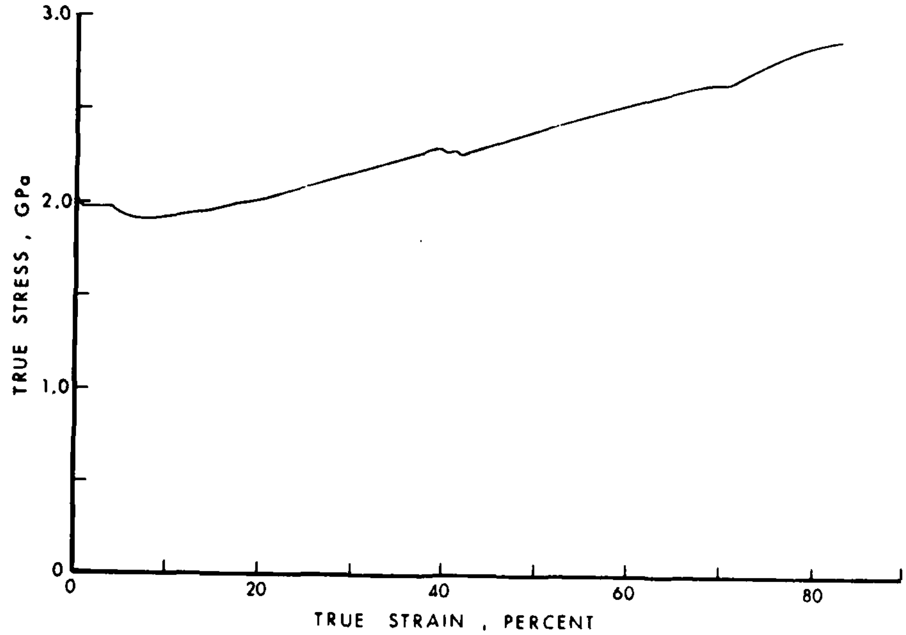

Figure 11. True Stress versus True Strain, to Rupture, for Precipitation Hardened 300 Maraging Steel in Tension, from Test T115.

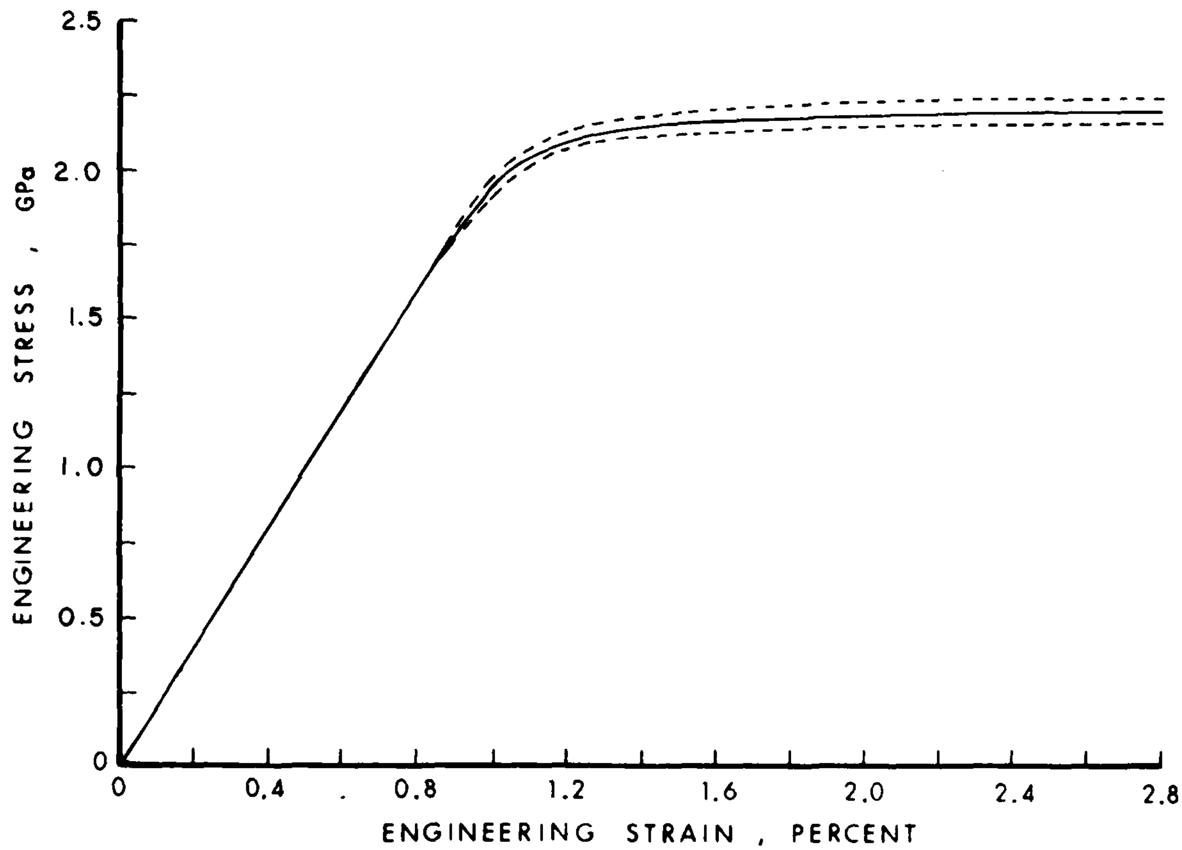

Figure 12. Average Engineering Stress versus Engineering Strain for Precipitation Hardened 300 Maraging Steel in Compression from Tests C111 thru C113.

VII. ACKNOWLEDGEMENTS

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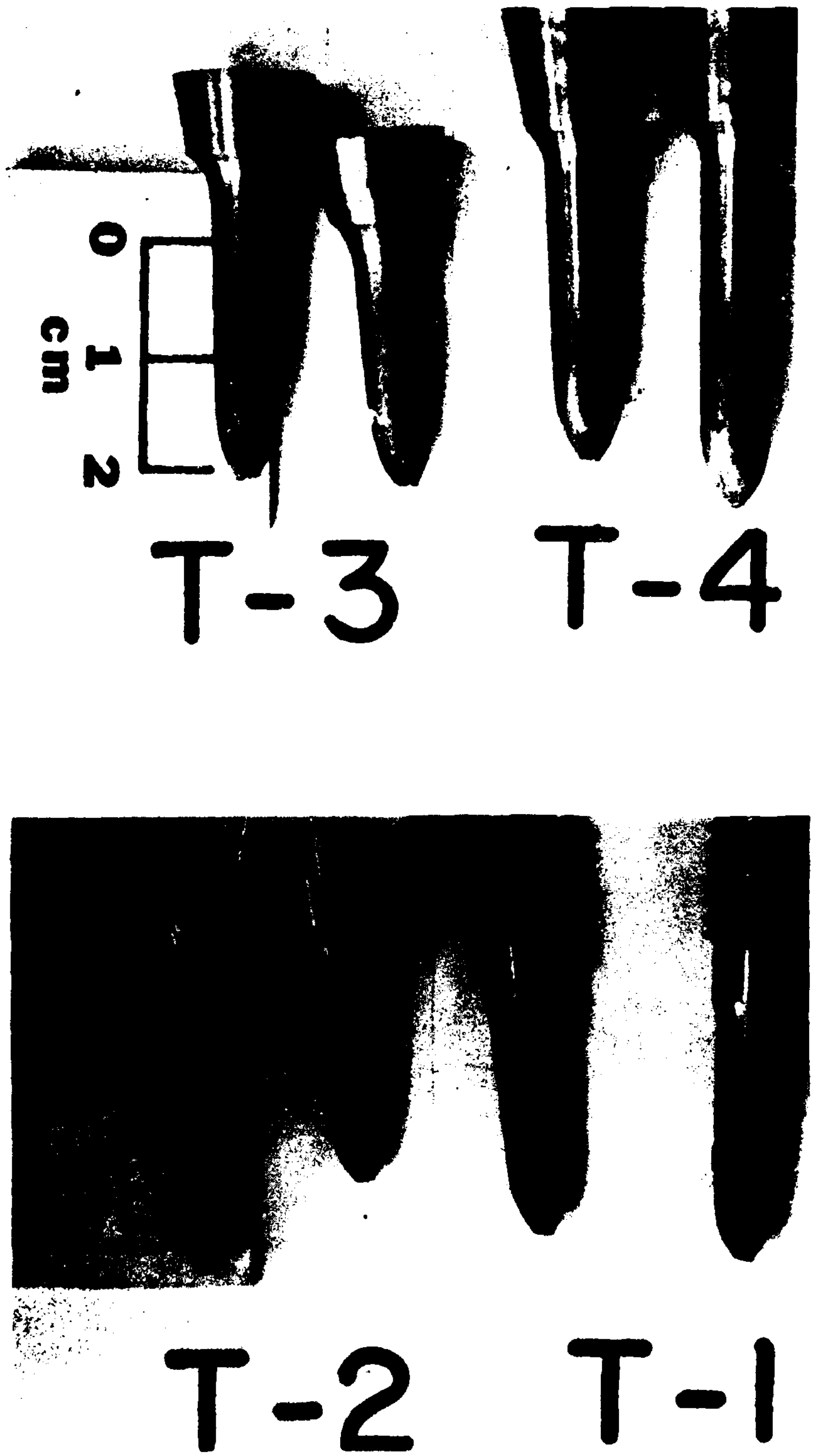

Figure 13. Post-test Ta-10W Tensile Specimens. T-3 is from test T108, T-4 from T110, T-2 from T107, and T-1 from T109.

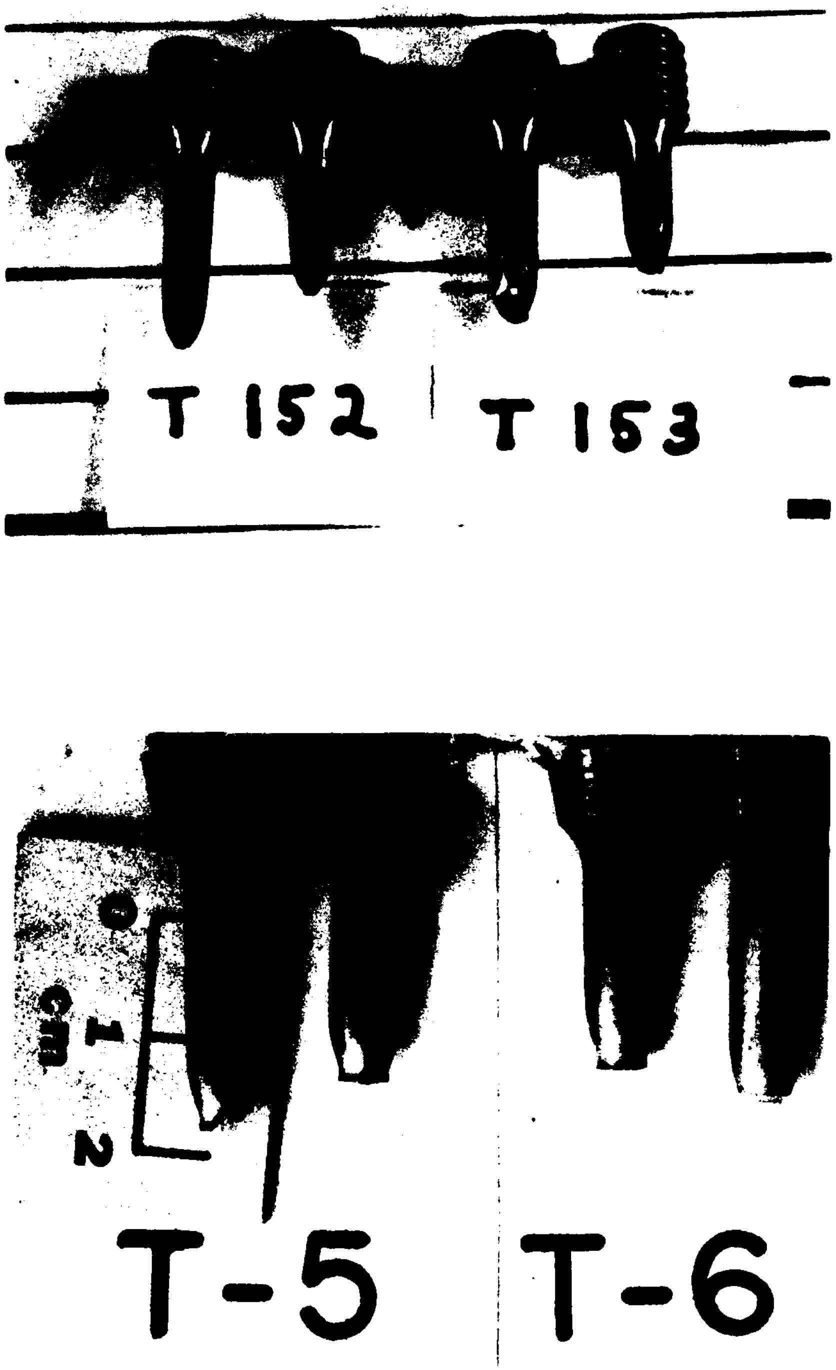

Figure 14. Post-Test Ta-10W and 300 Maraging Steel Tensile Specimens. The Ta-10W specimens from T152 and T153 are photographed inclined against a half-inch grid. The lower specimens are maraging steel, and are from tests T114 (T-5) and T115 (T-6).

REFERENCES

1. Murray, Jr., E.A., and Suckling, J.H., "Quasi-static Compression Stress - Strain Curves -- I, 1066 Steel," BRL Memorandum Report 2399, Ballistic Research Laboratories, Aberdeen Proving Ground, MD, July 1974, AD 922704L.

2. Murray, Jr., E.A., "Quasi-static Compression Stress - Strain Curves -- II, 7039 Aluminum," BRL Memorandum Report 2589, Ballistic Research Laboratories, Aberdeen Proving Ground, MD, February 1976, AD B009646L.

3. Benck, R.F., and Murray, Jr., E.A., "Quasi-static Compression Stress - Strain Curves -- III, 5083-H131 Aluminum," BRL Memorandum Report 2480, Ballistic Research Laboratories, Aberdeen Proving Ground, MD, May 1975, AD B004159L.

4. Benck, R.F., Filbey, G.L., and Murray, Jr., E.A., "Quasi-static Compression Stress - Strain Curves -- IV, 2024-T3510 and 6061-T6 Aluminum Alloys," BRL Memorandum Report 2655, Ballistic Research Laboratories, Aberdeen Proving Ground, MD, August 1976, AD B013221L.

5. Benck, R.F., and Filbey, Jr., G.L., "Elastic Constants of Aluminum Alloys, 2024-T3510, 5083-H131 and 7039-T64 as Measured by a Sonic Technique," BRL Memorandum Report 2649, Ballistic Research Laboratories, Aberdeen Proving Ground, August 1976, AD B012953L.

6. Benck, R.F., and DiBerardo, D.A., "Quasi-static Tensile Stress - Strain Curves -- I, 2024-T3510 Aluminum," BRL Memorandum Report 2587, Ballistic Research Laboratories, Aberdeen Proving Ground, MD, February 1976, AD B009639L.

7. Benck, R.F., and Robitaille, J., "Tensile Stress - Strain Curves -- II Rolled Homogeneous Armor," BRL Memorandum Report 2703, Ballistic Research Laboratories, Aberdeen Proving Ground, MD, November 1976, AD B016015L.

8. Benck, R.F., and Robitaille, J., "Tensile Stress - Strain Curves -- III Rolled Homogeneous Armor at Strain Rate of 0.42 s^{-1}," BRL Memorandum Report 2760, Ballistic Research Laboratories, Aberdeen Proving Ground, MD, June 1977, AD A014560L.

9. Wolf, J., and Brown, Jr., W.F., Ed., "Ta-10%W, Material Code 5402," Aerospace Structural Metals Handbook, 1976 Edition, Volume IV, AFML-TR-68-115, Mechanical Properties Data Center, Belfour Stulen, Inc., Traverse City, MI 49684, 1975, pp. 1-14, AD 737973.

10. Small, Louis, "Part I, Practice," Hardness -- Theory and Practice, 1960, Service Diamond Tool Co., Ferndale, MI 48220, pp. 483-484.

11. Application Data for Nickel Maraging Steels, VASCO Corporation, Latrobe, PA 15650, 1968.

12. Moore, T.D., Ed., Structural Alloys Handbook, Volume 2, 1976 Edition, Mechanical Properties Data Center, Belfour Stulen, Inc., Traverse City, MI 49684, Appendix C, pp. 1-7.

13. ASTM Commitee E-28 on Mechanical Testing, ANS Z165.13-1971, "Standard Methods of Tension Testing of Metallic Materials," American National Standards Institute, 1969.

14. ASTM Commitee E-28 on Mechanical Testing, ANS Z115.16-1973, "Standard Methods of Compression Testing of Metallic Materials at Room Temperature," American National Standards Institute, 1969.

15. ASTM Commitee E-28 on Mechanical Testing, ANS Z115.6-1967, "Standard Methods of Testing for Rockwell Hardness and Rockwell Superficial Hardness of Metallic Materials," American National Standards Institute, 1967.

16. Hetenyi, M., Ed., Handbook of Experimental Stress Analysis, John Wiley and Sons, Inc., New York, NY, 1950.

17. Hines, William W., and Montgomery, Douglas D., Probability and Statistics in Engineering and Management Science, Ronald Press, New York, 1972.

APPENDIX

Table A1. Engineering Strain and Engineering Stress for Ta-10W Specimens, Measured on Tensile Tests T108 thru T110

Test T108		Test T109		Test T110			
Strain (Photographic) (percent)	Stress (MPa)	Strain (Photographic) (percent)	Stress (MPa)	Strain (Extensometer) (percent)	Stress (MPa)	Strain (Extensometer) (percent)	Stress (MPa)
0.	0.	0.	0.	0.	0.		
0.67	96.7	.18	158.6	0.003	42.0	3.34	850.3
2.70	453.0	1.54	445.7	0.007	61.7	3.67	846.6
2.85	454.0	3.76	479.5	0.019	87.7	3.95	843.8
4.94	482.0	5.58	506.5	0.041	119.0	4.18	840.5
6.07	512.6	6.79	523.7	0.061	152.3	4.42	835.2
7.94	535.2	9.57	552.8	0.070	183.8	4.71	831.6
10.86	561.0	12.09	562.6	0.098	228.6	5.13	827.5
13.93	573.9	14.20	567.6	0.124	266.7	5.62	819.4
19.33	577.5	16.20	568.8	0.155	308.8	6.07	811.7
23.37	576.5	19.35	567.6	0.177	346.0	6.53	802.3
26.59	574.2	21.91	561.0	0.215	396.5	6.98	794.6
32.73	566.8	24.59	545.6	0.237	455.9	7.40	786.1
37.68	554.6	26.58	526.6	0.268	503.1	7.40	778.8
39.93	548.1	27.66	508.3	0.299	551.5	8.39	765.7
43.07	535.2	29.02	487.0	0.345	625.8	8.99	752.7
46.52	522.3	29.91	470.1	0.364	658.4	9.48	742.6
47.19	509.4	31.07	451.3	0.380	681.2	10.04	729.2
50.41	496.5	31.54	432.5	0.397	704.4	10.54	717.0
51.98	482.0	32.80	410.2	0.411	725.1	11.06	703.6
53.86	470.7	33.33	394.9	0.428	743.4	11.59	689.7
55.96	457.8	33.67	379.3	0.437	758.4	12.05	675.9
58.50	444.9	34.06	363.5	0.450	773.9	12.50	662.5
61.35	432.0	35.01	351.0	0.466	789.3	13.01	646.2
61.12	419.1	34.87	338.5	0.483	806.8	13.57	628.4
63.07	406.2	35.32	325.3	0.510	823.0	14.12	611.7
63.74	399.8	35.32	310.3	0.543	836.1	14.59	594.2
65.09	393.4	35.80	294.6	0.584	844.6	15.11	575.5
66.67	386.9	36.66	282.1	0.622	849.5	15.63	555.6
67.27	377.2	36.98	272.7	0.677	852.3	16.12	536.5
66.52	367.6	37.21	260.1	0.734	853.9	16.64	515.4
69.51	354.7	37.65	250.7	0.885	854.8	16.96	496.3
70.86	341.8	37.51	247.0	1.01	855.6	17.39	478.0
70.94	332.1	37.98	236.3	1.20	855.6	17.72	462.9
72.90	322.4	38.26	225.6	1.53	854.8	18.15	442.2
74.46	303.1	38.71	213.1	1.88	855.6	18.68	416.6
77.08	277.2			2.25	855.2	19.19	392.6
				2.69	853.9	19.67	366.6
				3.03	851.9	20.62	312.6

Table A2. Engineering Strain and Engineering Stress for 300 Maraging Steel Specimens, Measured Photographically on Tensile Tests T114 and T115.

Test T114			Test T115		
Stress (GPa)	Strain (percent)	Specimen Diameter (mm)	Stress (GPa)	Strain (percent)	Specimen Diameter (mm)
0.	0.	6.350	0.	0.	6.342
0.533	0.23	6.345	1.899	0.	6.342
1.833	0.70	6.340	2.040	1.59	6.342
2.019	3.89	6.238	2.029	2.45	6.342
1.966	5.29	6.203	1.967	3.75	6.327
1.941	5.44	6.172	1.931	6.42	6.284
1.920	5.83	6.132	1.899	7.00	6.215
1.895	7.62	6.152	1.869	7.51	6.210
1.865	8.32	6.116	1.836	8.81	6.190
1.833	9.49	6.071	1.792	11.70	6.152
1.827	10.11	5.984	1.766	12.49	6.116
1.783	13.06	5.519	1.757	12.92	6.078
1.743	15.55	5.484	1.725	14.37	5.994
1.709	17.34	5.357	1.693	15.02	5.916
1.678	19.36	5.220	1.677	15.23	5.809
1.641	20.76	5.128	1.646	16.68	5.730
1.603	21.77	5.047	1.616	17.83	5.491
1.571	23.56	5.001	1.583	18.70	5.344
1.532	25.97	4.854	1.553	19.85	5.217
1.494	27.92	4.818	1.532	20.07	5.202
1.409	30.33	4.696	1.519	20.94	5.174
1.387	31.49	4.580	1.494	21.44	5.159
1.365	31.73	4.488	1.472	22.09	4.986
1.319	34.14	4.366	1.377	28.01	4.625
1.269	34.76	4.346	1.361	28.95	4.575
			1.342	29.46	4.521
			1.315	30.40	4.468
			1.298	31.12	4.282
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