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DATE: February 12, 1958

SUBJECT: Resume of Information on Hydrogen in Titanium Alloys and its Implications to HRP

TO: G. M. Adamson

FROM: J. P. Hammond 6238

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Continued on page ii

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INTRA-LABORATORY CORRESPONDENCE

OAK RIDGE NATIONAL LABORATORY

To: G. M. Adamson

Date: February 12, 1958

From: J. P. Hammond

Re: Hydrogen in Titanium

The attached memorandum is a summary of available data on hydrogen in titanium and its implications to HRP. It was prepared from reports available at the Laboratory. The purpose of this memorandum is to outline these problems and to serve as a reference for the interested development engineers.

It should be pointed out that while the report only discusses titanium much of the data would also apply to zirconium.

J. P. Hammond

GMA:fl
Att.

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RESUME OF INFORMATION ON HYDROGEN IN TITANIUMALLOYS AND ITS IMPLICATION TO HRP

Joseph P. Hammond

INTRODUCTION

Hydrogen embrittlement in titanium, although first observed in laboratory investigations in 1951, was soon to occur in engineering service. Failures included the widespread breakage of formed titanium C-110M alloy (8% Mn) aft sections in the F-100 airplane in 1954, as well as cracking in forged Ti-150A spacer rings in the J-57. In June 1955 cracking occurred in the forged Ti-140A second stage compressor wheels of the J-73 aircraft engine. As a result of the extensiveness of these failures, the Air Force launched a crash program to investigate these failures and set up control measures.

Although other hydrogen effects are encountered, the particular type of embrittlement noted above has not been shown to be common to the all-alpha type alloys in which HRP is primarily interested. It is hoped that through appropriate selection of alloys, control of hydrogen limits, and design, failures from hydrogen embrittlement may be largely avoided in the project. To accomplish this, further work will need be done to determine the effects of hydrogen on mechanical properties of the alloys in which we are interested and to evaluate the extent of hydrogen contamination in- and out-of-pile application. Additional work along these lines is being formulated and will be prosecuted as expeditiously as possible.

The purpose of the present report is to summarize the available information on the nature of hydrogen embrittlement in titanium, on the control of hydrogen and on its effects on properties. While this report deals with titanium, it should be pointed out that most of the data would apply equally well to zirconium. For more extensive information on the subject, reference may be made to the following reports, on file in HRP Metallurgy:

1. Effect of Hydrogen on the Properties of Titanium and Titanium Alloys, TML Report 27, Dec. 1955.
2. Survey of The Problem of Delayed Cracking in Formed Titanium Parts, TML Report 7, June 1955.
3. The Influence of Hydrogen on Delayed Failure in Titanium Alloys, WADC Report 57-30, Feb. 1957.
4. The Effect of Hydrogen on the Embrittlement of Titanium at 300°C, a Thesis by J. J. Prisliger, University of Florida, Aug. 1956.

TYPES OF HYDROGEN EMBRITTLEMENT IN TITANIUM ALLOYS

Two distinctly different types of hydrogen embrittlement are observed to occur in titanium alloys. Alpha-type alloys are more susceptible to hydrogen embrittlement at impact rates of loading. The most important variables in this type of embrittlement are hydrogen content, testing temperature, notches, and strain rate. A ductile to brittle transition temperature in impact testing is observed, much as is characteristic of steels. A notch-bend impact test, such as the Charpy test, is the most sensitive means for evaluating this type of embrittlement.

Alpha-plus-beta alloys may show a susceptibility to the impact type of embrittlement, mentioned above, as well as a strain-aging type of embrittlement. This strain-aging type of embrittlement becomes most pronounced at slow strain rates, which suggests that hydrogen diffusion plays a significant role. Material so affected can fail at a fraction of its yield strength while under static load. It is this type of embrittlement which produced the aircraft part failures mentioned earlier. Statically loaded, notched-specimen tests, such as stress rupture tests, are most effective in evaluating this type of embrittlement. This embrittlement, too, has its counterpart in steel and is referred to as "delayed cracking."

The cause of the impact embrittlement in alpha alloys is considered to be the presence of brittle hydride flakes. Whereas commercial titanium may have a solubility limit as high as 2000 ppm at 320°C, at room temperature the solubility is restricted to only a few ppm. Consequently, hydrogen absorbed in solution at elevated temperature may be rejected as brittle hydride flakes on cooling. Fig. 1 illustrates the flake-like nature of hydrides formed in an all-alpha alloy.

One way to combat impact embrittlement in alpha alloys is to alloy with the alpha stabilizers aluminum and tin. Binary alloys with 5 w/o Al or 10 w/o Sn have hydrogen solubilities which do not become restricted on cooling to room temperature. This is reflected in an increased hydrogen tolerance of the alpha titanium in impact tests since there is little opportunity for brittle hydride to precipitate. A more questionable method of countering impact embrittlement in alpha alloys is through small beta particle retention.* The beta phase, having a high solubility for hydrogen, is considered to getter it from the alpha phase, preventing precipitation of hydride.

*This method is questionable because retained beta in such alpha alloys is reported to be subject to decomposition at intermediate temperatures, precipitating embrittlement-producing Ti_2Fe plus hydride.

The mechanism of the strain-aging type of embrittlement, common to alpha-beta alloys, appears to be one wherein crack initiation is influenced by a critical hydrogen and stress concentration, followed by a slow propagation of the crack, which is hydrogen-diffusion dependent. While it is somewhat controversial whether hydride actually forms at the root of the notch as the crack propagates, the crack ordinarily follows the alpha-beta interfaces and is considered to progress as hydrogen is diffused in the beta phase. Investigations of "delayed cracking" in alpha-beta alloys have indicated that strength level, notch acuity, hydrogen content, and microstructure may influence the susceptibility and range of stress at which failure occurs.

Work at Battelle, involving notched and unnotched tensile test as well as notched impact tests, has shown that the hydrogen tolerance in alpha-beta alloys may be substantially improved with molybdenum additions and possibly with vanadium.

WITH THE VIEW TO ATTAIN MAXIMUM STABILITY OF MICROSTRUCTURE AND MECHANICAL PROPERTIES AND AFFORD GOOD WELDABILITY, HRP POLICY WILL BE TO USE ALPHA-TYPE ALLOYS SOLELY. WHILE IT IS NOT EXPECTED THAT THE STRAIN-AGING TYPE OF HYDROGEN EMBRITTLEMENT WILL BE INVOLVED, THIS TYPE, AS WELL AS THE IMPACT TYPE EMBRITTLEMENT, IS BEING INVESTIGATED IN THE ALLOYS CONSIDERED FOR HRP USE. At present, the alpha alloys Ti-55A and Ti-110AT (5Al-2.5Sn) are being considered for use.

SOURCES OF HYDROGEN

A listing of the various sources of hydrogen is given below:

- (1) In sponge form.
 - (a) Water vapor in sponge preparation chamber.
 - (b) Acid leaching of sponge.
 - (c) Hygroscopic action of $MgCl_2$ of sponge during storage.
- (2) During melting.
 - (a) Water vapor in furnace.
- (3) During mill and shop fabrication.
 - (a) Water vapor or reducing conditions in heating and annealing furnace atmospheres.
 - (b) Descaling in sodium hydride baths.
 - (c) Pickling in acid solutions.

The hydrogen content of the sponge, from which all commercial grades of titanium alloys are presently made, and the hydrogen pickup in descaling and pickling operations are believed to be the main sources of hydrogen contamination in titanium. Coupled with the above is the question of hydrogen pickup during loop and reactor service.

Three general types of chemical treatments are being used to remove scale formed on titanium during mill and fabrication processing:

- (1) Acid pickling.
- (2) Caustic bath.
- (3) Sodium hydride bath.

The first of these is most applicable to our operations since treatment of large components in molten baths is not altogether practical. While work at Battelle has shown that the Virgo method, a caustic bath, can be operated with little or no hydrogen pickup, unfortunately the surface is not left as smooth and lustrous as with the other methods. Rem-Cru has shown that the hydrogen pickup in the widely used nitric-hydrofluoric acid bath can be considerably decreased by raising the ratio of nitric to hydrofluoric acid. The relation between hydrogen pickup and nitric acid concentration for a 2 per cent hydrofluoric bath is shown in Fig. 2. This data suggest that the commonly used 10 per cent nitric-2 hydrofluoric pickling bath was partly responsible for the high hydrogen concentration of materials produced in the past. Although there will be a tendency for baths to fume at higher nitric acid concentrations, a solution containing 20 per cent nitric acid is recommended as the best practice.

For low-temperature operations such as acid pickling, diffusion will be slow and hydrogen will remain at the surface rather than distribute uniformly throughout the part. Also, the rate of chargeup for thin sheet would be substantially greater than for bulky bar stock because of a high surface-to-volume ratio. When in the form of hydride, hydrogen localized at the surface of a part can be particularly damaging since the surface is generally the location of high stress and where cracks originate.

Figure 3 illustrates a surface enrichment with hydrogen by pickling, referred to above. The descaling time and temperature have been extended beyond normal limits to improve the accuracy of the analyses. The hydrogen contents obtained at the surfaces here would be sufficiently high to produce embrittlement. However, in commercial pickling the extent of surface hydrogen enrichment would be difficult to evaluate because of the short times used and consequent small amount of metal affected.

EFFECTS OF HYDROGEN

Since the alpha-beta alloys have been excluded for HRP use, information given below relates primarily to alpha-type alloys and consequently to the type of embrittlement which is depicted at impact speeds of loading.

Mechanical Properties

It has been reported that thermal stability in titanium alloys is deleteriously affected by hydrogen. This means that load carrying capacity is depreciated with elevated temperature exposure as a result of microstructural changes in the alloy. Structurally the alpha alloys are more stable than the alpha-beta alloys and consequently are less affected by this manifestation of hydrogen contamination.

Unalloyed Titanium--The important variables in the impact embrittlement associated with alpha-type alloys are hydrogen content, testing temperature, notches, and strain rate. The single and combined effects of hydrogen, a notch, and testing speed, on transition temperature are shown schematically in Fig. 4. These results are based upon tensile tests conducted on unalloyed high-purity titanium. The drawings show that the transition temperature is raised by:

- (1) increase in hydrogen content
- (2) increase in strain rate
- (3) introduction of notch.

For a given hydrogen level, the greatest embrittlement occurs at impact speed and with a notch as shown in the lower right graph.

The effect of hydrogen on the mechanical properties of titanium of the 55,000-psi-yield strength class (made from sponge) is quite similar to its effect in relation to high-purity titanium. Fig. 5 shows tensile and Vickers hardness data for A-55 titanium as a function of hydrogen content. The elongation and reduction-in-area values decrease to about 10 per cent at 10 atomic per cent (approximately 2100 ppm) hydrogen. Work at Battelle with micro tests has given a notch-bend impact strength of 39 inch pounds for hydrogen-free A-55 titanium at room temperature. However, at 200 ppm hydrogen, where the toughness would be expected to be quite low, the room-temperature impact energy obtained, 10 inch pounds, was as high as that for high-purity titanium with 200 ppm hydrogen. This unexpected high impact value was attributed to retained beta in the A-55 alloy. It was concluded that the iron-stabilized retained beta in the commercial material alleviated the embrittlement by acting as a hydrogen getter. Additional data appears in the literature supporting the gettering action of the beta phase. No data is at present available showing the creep or stress rupture properties of unalloyed titanium as a function of hydrogen.

The shape of the solubility limit curve for hydride in unalloyed titanium suggests the possibility of improving the notch-bend impact strength of hydrogen-containing titanium by putting the hydrogen in solution in the alpha phase. Figure 6 shows the results of a Battelle investigation of such a solution treatment for the commercial A-55 alloy. The results for high-purity titanium are similar. Observe that the solution treatment improves the toughness, as indicated by comparison of the slow-cooled and as-quenched data. The microstructures of the water-quenched samples, however, indicated that the hydride had not been retained in solution but that the improvement in toughness resulted from a redistribution of the hydride phase as a very fine uniform dispersion. Unfortunately, the improvement in toughness is not permanent, and the toughness of the solution-treated material decreases on aging at room temperature. The toughness of the solution-treated A-55 alloy at approximately 0.25 atomic per cent (50 ppm) hydrogen decreased below that of the slow-cooled material, after only one week. At the higher hydrogen levels, the benefits of the solution treatment are so nominal as to make the treatment of questionable value.

Alloys Containing Alpha Stabilizers--The available data on mechanical properties for alpha-type alloys cover only experimental materials. Equilibrium data for 5 Al and 10 Sn alloys show that these binary additions result in increased solubility of hydrogen at low temperatures. This increase in solubility is reflected in an increase in hydrogen tolerance of alpha alloys in notch-bend impact tests. This is shown in Table 1. The notch-impact strength for the Ti-10Sn alloy remains relatively unaffected through 50 ppm hydrogen. The 5Al alloy shows no embrittlement up to 180 ppm. Hydride flakes have been found in the Ti-5 alloy at 310 ppm hydrogen indicating that the material would become embrittled at this level. The data on the Ti-5 Al-0.2 oxygen alloy indicate that oxygen diminishes the effect of aluminum as a booster of hydrogen tolerance.

The above impact information on the 5Al and 10Sn alloys suggests prospects of a high hydrogen tolerance in the A-110AT (5Al-2-1/2Sn) alloy in which the project is interested. This will be investigated.

Forming

Most forming operations on titanium are carried out at relatively high strain rates, i.e., at rates above about 0.1 in./in./min. Rates of this order are in excess of that at which difficulty is had with the strain-aging type of hydrogen embrittlement. On the other hand, alpha-beta alloys with hydrogen contents at 150 ppm and higher may be susceptible to strain aging embrittlement subsequent to forming as a result of stresses residual from the forming operation or applied in service.

For alpha alloys of the 55,000 psi class, no forming difficulties associated with hydrogen have been reported. The observance of a 150 ppm maximum hydrogen content for both alpha and alpha-beta sheet alloys should greatly minimize any difficulty in forming as well as the tendency for "delayed cracking."

Heat Treatment

The complete effects of hydrogen on the heat treating processes used for titanium alloys are not well understood. Since structural response to heat treatment for the alpha alloys, as a class, is simpler than for the alpha-beta alloys, opportunities for difficulties arising from the effects of hydrogen would be less for the former. Of several effects of hydrogen reported in the literature, two of particular interest will be mentioned.

First, the beta-stabilizing action of hydrogen can result in a significant lowering of the beta transus temperature and in so doing affect the mode of alpha precipitation in heat treatment. In the Ti-8 Mn alloy this has resulted in a high incidence of Widmanstatten structure formation.

Second, hydrogen, like other interstitial elements, is believed to accelerate the transformation kinetics of titanium. This no doubt is the mechanism by which hydrogen induces service thermal instability in titanium alloys.

Joining

Available data indicate that the presence of hydrogen offers no significant difficulty in the fusion welding of titanium, although the effects relative to the transformation mechanisms and kinetics, cited above, may be present. Instead of hydrogen being picked up during arc welding, there are data to indicate that hydrogen is lost from the weld zone during welding.

CONTROL OF HYDROGEN

Control of hydrogen contamination may be accomplished in the following general ways: (1) modification or close control of the production and fabrication processes where hydrogen contamination may be significant; (2) removal of hydrogen by vacuum annealing the finished product; (3) preventive measures designed to minimize hydrogen contamination during service.

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Production and Processing

Close control of the sources of hydrogen contamination is the most important of the methods cited above for eliminating the effects of hydrogen. Unfortunately, however, except for fabrication and final pickling operations, control of these steps is largely in the hands of the four major producers of titanium.* These companies are cognizant of the hydrogen problem, and competition between them may be expected to result in near uniformity in the quality of the products as respects hydrogen, as well as to result in possibly lower hydrogen limits in the future. The sponge used by some of the firms is lower in hydrogen and less susceptible to pickup than that used by others, while the other firms employ melting processes which are more advantageous from the standpoint of hydrogen removal. The net result is that hydrogen content may not vary greatly between products coming from the several companies.

Without distinguishing between the four major suppliers, a survey was made by the Air Force of the hydrogen contents of materials arriving at aircraft and engine manufacturers' plants from September 1 to December 1, 1955. Results of hydrogen analyses showed that about 15 per cent of 561 alloy sheet samples examined (96 per cent were Ti-8 Mn alloy) exceeded the Air Force specification limit for hydrogen of 150 ppm. The average content for the sheet samples was 116 ppm. For bar and forging stock, the hydrogen limit, 125 ppm, was exceeded by only about one per cent for a total of 225 samples; and the average hydrogen content was 56 ppm.

HRP specifications for the A55 and 5 Al-2-1/2 Sn alloys at present prescribe a maximum content for hydrogen of 100 ppm; however, as yet vendors will not guarantee less than 150 for plate and 125 for bar. These limits will be lowered as the producers agree to lower limits.

It is recommended in the interest of hydrogen control that electric muffle furnaces be employed for heat treating titanium alloys where applicable. When furnaces with combustion atmospheres are employed, the atmosphere should be slightly oxidizing. Where scales are superficial and sand blasting can be used for scale removal, this method is preferred. When employing the 2 per cent HF-nitric acid pickling bath, a 20 per cent concentration of nitric acid is recommended.

* Rem-Cru, TMC, Mallory-Sharon, and Republic

Hydrogen Removal

The pressure dependence of the solubility of hydrogen in titanium makes possible the removal of hydrogen by vacuum annealing. While very effective the process suffers the disadvantage of being expensive and often the available facilities seriously limit the sizes of parts which can be treated. Notwithstanding, North American Aviation has just installed a furnace at Downey, California, for vacuum annealing titanium, which has a working chamber in excess of 14 ft. long and 6 ft. in diameter.

Alpha-type alloys lend themselves more suitably to vacuum annealing than alpha-beta alloys because their microstructures are more stable at the temperature of treatment. Caution must be exercised in annealing components fabricated of alpha-beta alloys since phase changes will result in mechanical property changes as well as dimensional alteration.

Factors which govern the removal of hydrogen by vacuum annealing are the hydrogen pressure-solubility relation and the diffusion rate of hydrogen in titanium. Battelle data showing the low-pressure solubility relation for hydrogen in commercial A-55 alloy are given in Fig. 7. The A-55 data show that at constant pressure, increasing the temperature gives a progressive decrease in hydrogen solubility between 715 and 815°C. However, at 865°C the solubility increases, presumably because of an increase in the amount of beta phase (resulting from iron impurity). These results would indicate that an optimum temperature for vacuum annealing, based on solubility considerations alone, exists at around 815°C for the A-55 alloy.

For a given geometrical shape the diffusion rate of hydrogen will govern the speed of hydrogen removal. Thus the higher the annealing temperature the faster will be the rate of removal. This is borne out in the Battelle data on the A-55 alloy in Table 2. Increasing the cross-sectional dimension of a shape will increase the time required for removal, as shown in this table. The time required for degassing various rod sizes increases approximately with the square of the diameter.

The presence of oxide films has been shown to have an effect on rate of hydrogen removal. While some films have been shown to increase the rate of hydrogen removal, an oxide film formed on high-purity titanium at 790°C prevented the removal of hydrogen.

With respect to HRP practice, there is the question of whether the hydrogen levels which would be attained in components fabricated from alpha-type alloys would be sufficiently high to warrant vacuum annealing. At the present time it is felt that the threat of impact embrittlement would not be sufficiently serious to necessitate it insofar as reasonable control is exercised in minimizing hydrogen pickup during fabrication.

Pickup In Service

The major concern at present is not the degree of contamination which will result from processing the constructional material and fabricated component, but rather the extent to which hydrogen levels will increase during exposure in service. Hydrogen has been absorbed to high concentrations (embrittlement was pronounced) in certain functional titanium parts while operating in hydrogenated slurry loops. The mechanism by which the hydrogen is introduced is not known. The question of whether hydrogen can be picked up by titanium in uranyl sulfate solutions has not as yet been settled for out-of-pile or in-pile exposures. It would appear that out-of-pile pickup, if present, is only very slight. In the case of the few in-pile tests which have been conducted, questions have arisen as to the adequacy of the procedures and methods of analyses used.

It is hoped that in the near future methods may be evolved for establishing the extent of hydrogen pickup both for in-pile and out-of-pile soup exposures. With adequate procedures for determining hydrogen pickup, a number of artificially induced films will be investigated for inhibiting hydrogen pickup. Since such treatments would be for use on components preliminary to assembly into service units, simple immersion procedures would be preferred. A number of films developed for producing anti-galling and wear-resisting qualities in titanium meet the requirement of simplicity and will be examined.

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9. G. A. Lenning, C. M. Craighead, and R. I. Jaffee, "The Effect of Hydrogen on the Mechanical Properties of Titanium and Titanium Alloys," Third Summary Report, Contract No. DA-33-019-ORD-938 (July 31, 1954).

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(500X)

FIGURE 1 MICROSTRUCTURE OF MST GRADE III TITANIUM (UNALLOYED, 90,000 psi Y.S. CLASS) BEFORE AND AFTER EXPOSURE TO HYDROGEN EMBRITTLING SERVICE. THE PART IS A PUMP SEALING RING WHICH HAD SEEN EXTENDED SERVICE IN A HYDROGENATED, THORIA SLURRY LOOP--LEFT, AS-RECEIVED, CONTAINING 230 ppm HYDROGEN; RIGHT AFTER SERVICE, 2380 ppm HYDROGEN. WHILE PRESENT, THE HYDRIDES ARE NOT READILY OBSERVABLE IN THE AS-RECEIVED STRUCTURE.

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FIGURE 2 HYDROGEN ABSORPTION BY REM-CRU C-110M SHEET
IN NITRIC-HYDROFLUORIC ACID PICKLING BATHS AS
A FUNCTION OF NITRIC ACID CONTENT (5)

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FIGURE 3 HYDROGEN DIFFUSION IN FORGED TITANIUM BAR RESULTING FROM PICKLING IN 1 PER CENT NITRIC-HYDROFLUORIC BATH AT 700°F⁽⁵⁾

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FIGURE 4 SCHEMATIC DRAWING OF THE EFFECT OF HYDROGEN, TESTING SPEED, AND A NOTCH OF THE DUCTILE-TO-BRITTLE TRANSITION TEMPERATURE BASED ON DATA FOR UNALLOYED HIGH-PURITY TITANIUM (6)

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FIGURE 5 EFFECT OF SOLUTION TREATMENT AND ROOM-TEMPERATURE AGING ON THE NOTCH-BEND IMPACT STRENGTH OF HIGH-PURITY TITANIUM (?)

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FIGURE 6 EFFECT OF SOLUTION TREATMENT AND ROOM-TEMPERATURE AGING ON THE NOTCH-BEND IMPACT STRENGTH OF COMMERCIAL A-55 TITANIUM ⁽⁶⁾

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FIGURE 7 PRESSURE VERSUS HYDROGEN SOLUBILITY FOR
COMMERCIAL UNALLOYED TITANIUM (A-55) AND
THE Ti-8 Mn (C-110M) TITANIUM ALLOY (9)

TABLE 2. DEGASSING DATA FOR A-55 TITANIUM⁽¹⁵⁾

Time, seconds	<u>Effect of Temperature on the Rate of Degassing</u>	
	Per Cent of Initial Hydrogen Content ^(a) Removed at Temperature Indicated	
	715 C	815 C
500	19	29
1,000	34	56
2,000	55	83
3,000	67	90
4,000	75	93
5,000	81	95
6,000	84	97
7,000	87	--

Time, seconds	<u>Effect of Rod Diameter on the Rate of Degassing</u>		
	Per Cent of Initial Hydrogen Content ^(a) Removed at 815 C from Various Diameters		
	0.125 In.	0.250 In.	0.500 In.
500	64	29	12
1,000	81	56	22
2,000	92	83	40
3,000	95	90	51
4,000	--	93	58
6,000	--	97	65
8,000	--	--	70
10,000	--	--	73
12,000	--	--	75
14,000	--	--	77

(a) Initial hydrogen content, 43 ppm.

TABLE 1. EFFECT OF HYDROGEN ON THE MECHANICAL PROPERTIES OF ALPHA-STABILIZED TITANIUM ALLOYS⁽¹³⁾

Hydrogen Content		Tensile Properties (Testing Speed = 0.005 Inch per Minute)					Notch-Bend Impact Strength at Indicated Temperature, in-lb			
PPM	Atomic Per Cent	Reduction in Area, per cent	Elongation, per cent in 1/2 inch	Proportional Limit	0.2 Per Cent Offset Yield Strength, psi	Tensile Strength, psi	-196 C	-40 C	25 C	100 C
<u>Titanium-10 Per Cent Tin Alloy</u>										
10	0.05	64	12 ^(a)	57,000	62,000	75,000	40	47	53	53
50	0.24	53	22	57,000	67,000	18,000	37	43	55	55
100	0.47	62	24	81,000	73,000	81,000	3	11	22	41
190	0.90	58	24	47,000	70,000	79,000	2	6	17	26
<u>Titanium-5 Per Cent Aluminum Alloy</u>										
10	0.05	41	12 ^(b)	74,700	--	95,000	40	43	40	49
50	0.24	44	26	73,000	85,000	98,000	35	39	43	50
95	0.45	49	22	76,000	91,000	101,000	35	45	45	45
180	0.90	49	18	--	--	111,000	34	44	44	39
<u>Titanium-5 Per Cent Aluminum-0.2 Per Cent Oxygen Alloy</u>										
10	0.05	46	14 ^(b)	101,000	106,000	118,000	9	26	29	30
50	0.24	45	26	105,000	--	122,000	10	24	28	30
95	0.45	48	22	110,000	--	124,000	9	17	30	29
190	0.90	40	30	118,000	--	127,000	9	16	26	30

(a) Fractured in gage marks.

(b) Fractured outside gage marks.