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TITANIUM—A PROSPECTIVE METAL FOR AIRCRAFT

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ABSTRACT

This paper briefly describes the suitability of Titanium to aircraft construction. The mechanical properties of the metal have been compared with those of other materials which are commonly used in aircraft construction. The general engineering value of the metal under service conditions is also indicated.

Introduction.

The development of Titanium and its alloys as useful engineering metals is one of the most significant present day progress in the field of metallic materials. Titanium is about two-third as heavy as steel, weighs 283·5 lbs. per cu. ft. (specific gravity 4·54) and is a little less than twice as heavy as aluminium. It has a high tensile strength and excellent corrosion resistance. It challenges aluminium and steel as a structural material for aeroplanes, rockets, guns, armour and vehicles of land and sea.

In order to use a material in aircraft construction, the following properties should be carefully investigated :

1. Strength weight ratio.
2. Buckling strength (Bending and Compression).
3. Fatigue and Impact strength.
4. Properties at high temperature.
5. Creep and Stress-rupture.
6. Shear strength.
7. Corrosion resistance.
8. Ease of fabrication, and
9. Availability.

Strength-Weight Ratio

The most important factor which governs the choice of the material for aircraft construction is its strength-weight ratio. The material should have the desired strength for minimum weight. Titanium, in particular, has a high strength-weight ratio as can be seen from the table No. 1. In this table the weights of tension material required to resist a given load have been compared as a product of the inverse ratio of their ultimate strength F, and the ratio of the weight per cubic inch, w.

$$\frac{W_1}{W_2} = \frac{w_1}{w_2} \times \frac{F_2}{F_1}$$

where W_1 and W_2 represent the weight of tension members of different materials resisting the same load.

The values in column 6 of the table indicate that Titanium is superior in strength-weight ratio to 24S-T and 75S-T aluminium alloys which are at present the most versatile materials in the aircraft construction.

Buckling Strength (Bending and Compression)

These properties have also been illustrated in table No. 1. For the comparison of the materials resisting bending moments, a flat sheet of thickness " t " has been assumed to resist a bending moment M per unit width as shown in the figure (a). The bending moment will be

$$F = \frac{MY}{1} = 6M/t^2$$

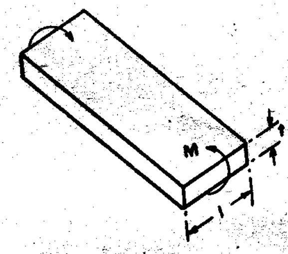

Fig. (a)

The required thickness will, therefore, be $t = \sqrt{\frac{6M}{F}}$

and the weight per sq. in. will be $W = tw = w\sqrt{\frac{6M}{F}}$

Therefore, the ratio of the weights of the sheets of two different materials resisting the bending moment will be

$$\frac{W_1}{W_2} = \frac{w_1}{w_2}\sqrt{\frac{F_2}{F_1}}.$$

Similarly the materials resisting buckling or compression loads have also been considered. A flat sheet of thickness ' t ' resisting a load P lbs. per unit width, is assumed to buckle as a long column. The buckling will be approximately

$$P = \pi^2 EI/L^2 = \pi^2 Et^3/12L^2 \quad \text{or } t = \sqrt[3]{\frac{12PL^2}{\pi^2 E}}.$$

For the two materials resisting the same load if the values of P and L be the same, the ratio of the weights can be calculated as

$$\frac{W_1}{W_2} = \frac{w_1}{w_2}\sqrt[3]{\frac{E_2}{E_1}}.$$

In table No. 1, the weight-to-weight ratio of all important aircraft sheet materials is compared in tension, bending and compression with 24S-T aluminium alloy which is at present mostly used in this industry.

TABLE I

Material in Sheet Form	Ultimate Tensile Strength $F \times 10^3$ Psi Approx	Elongation percent in 2 in. sample	Weight in Lbs./In.^{3}	Modulus of Elasticity $E \times 10^6$ Psi	Ratio of Wt. To the Wt. of 24 S-T Al. Alloy		
					Tension $\frac{w_1}{w_2}\frac{F_2}{F_1}$	Bending $\frac{w_1}{w_2}\sqrt{\frac{F_2}{F_1}}$	Compression Bucking $\frac{w_1}{w_2}\sqrt[3]{\frac{E_2}{E_1}}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
24 S-T Al. Alloy ..	66·0	20·0	0·100	10·5	1·00	1·00	1·00
75 S-T. Al. Alloy ..	77·0	13·0	0·101	10·4	0·87	0·93	1·01
Titanium (Hard) ..	125·0	15·0	0·162	15·0	0·84	0·85	0·70
Stainless Steel ..	185·0	15·0	0·286	26·0	1·02	1·72	2·12
Magnesium Alloy ..	40·0	6·0	0·065	6·5	1·07	0·84	0·77
Laminated Plastic	30·0	..	0·050	2·5	1·10	0·74	0·83
Spruce Wood ..	9·4	..	0·016	1·3	1·09	0·42	0·31

For the materials listed in this table, the ultimate tensile strength F, and the modulus of Elasticity E, are almost proportional to the density w. The weight ratios for tension members in the column (6) do not vary greatly. For members in bending, however, the materials with lower density have distinct advantage (column 7), and even greater in compression buckling (column 8), but Titanium appears to be an exception to this generalisation. Though it has a relatively higher density than the other aluminium and magnesium alloys, still as far as the deadweight reduction is concerned it has an advantage since for designing members in tension, compression and bending lesser material is required which ultimately increases the payload of the aircraft by reducing the dead-weight considerably. For example in the axial flow compressor of an aircraft gas-turbine where steel blades are being used at present, the change to titanium alloy blade would save 40% of the blade weight if only this metal substitutes the former one. As the titanium alloy blades could be thinner at the roots than the steel blades, because of reduced centrifugal loading, the weight might be reduced by even 50 per cent. A much lighter drum may be used due to the reduction in the weight of the blades and a pound of titanium used to replace two pounds of steel in the compressor blade might save more than its own weight in the drum ; Hanink had quoted a figure of five pounds of engine weight saved through the use of one pound of titanium in the compressor rotor blades.

Fatigue and impact strength

Aircraft engineers have been anxious to have dependable and reproducible fatigue values of the polished and notched specimens of the commercially available metals. The S.N. curve in figure No. 1, according to earlier investigations shows the endurance limit to be at 55,000 psi at 10 million cycles where the material has the tensile strength of 125,000 psi and 0·2 per cent offset yield strength of 110,000 psi. It was, however, found later that titanium has extremely high polished fatigue value but more important than this is the detailed work on notch specimens.

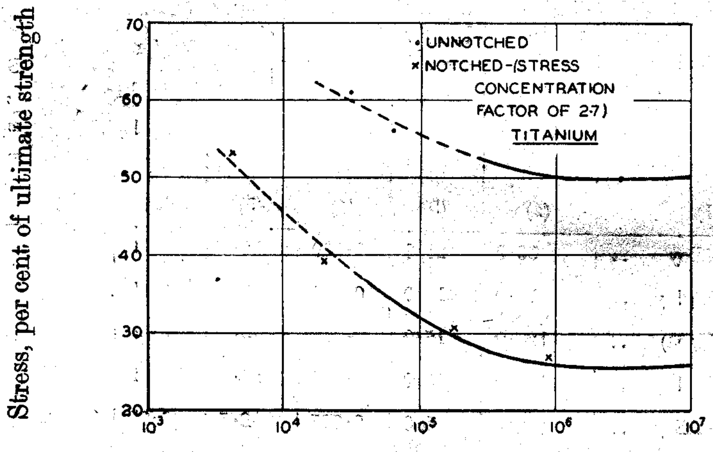

FIG. 1

A 60° Notch, 0·043 inches deep, having a root radius of 0·01 inch was used for the investigation and comparison of the fatigue strength of a number of metals. The results are shown in figure No. 1A.

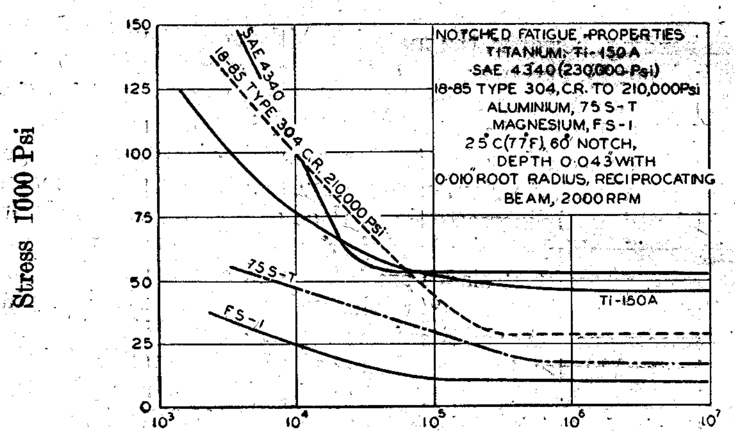

FIG. 1A

It can be seen that titanium is superior in notch performance to aluminium and magnesium alloys and competes fairly well with very strong steel alloys.

The shock-resistance or impact strength of the titanium is about 18 ft. lbs. at room temperature, but goes on increasing with the rise of temperature so much so that at 400°F, it is about 38 ft. lbs. (Fig. No. 2) and the fracture is ductile while at ordinary temperature it is brittle. It is in fact a great advantage for the aeroplanes because as the speed of the plane increases the temperature of the wings, fuselages etc. rises due to the impact of air which becomes stronger and more frequent. The design engineers, therefore, anticipated the use of the titanium in those parts which are subjected to severe service shocks.

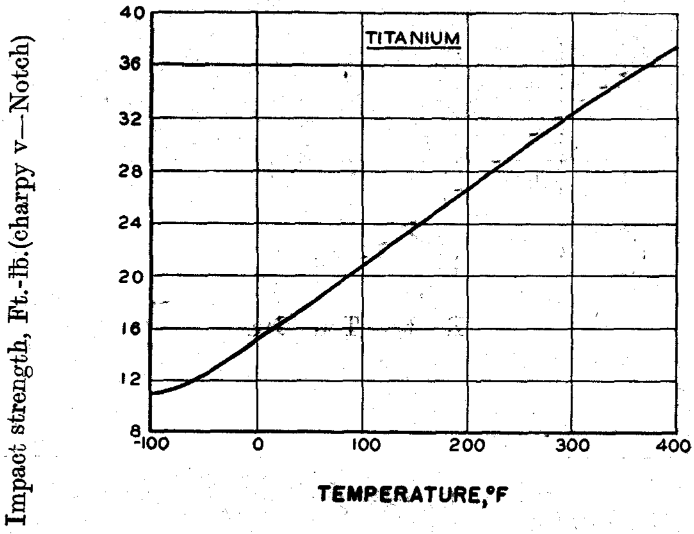

FIG. 2

Heat treatment studies on commercially pure titanium shows a marked improvement on the impact properties. The quenched and tempered samples withstand 35 ft. lbs. of energy absorption against 17 ft. lbs. ordinarily.

Properties at high temperature.

One of the most attractive features of titanium is its strength at high temperatures upto 1000°F. This property is especially useful for high speed aeroplanes. At supersonic speeds there is aerodynamic heating due to the friction of air sweeping over the wings and along the fuselage. Since aluminium alloys get brittle and have poor strength at 600°F and above, stainless steel has been introduced but it adds up the weight. Titanium, with low specific gravity and high elastic properties upto 800°F bridges the gap between aluminium and steel (fig. 3A). It seems to be tipped for covering rockets, guided missiles and space ships, if they become a reality in time to come.

Creep and stress rupture

An important characteristic of any structural metal is its creep rate ; the amount of gradual plastic flow, or permanent elongation, induced by a combination of high temperature and steady stress below that required to produce a permanent set as determined by short-time test at the same temperature. The creep behaviour of this metal, considering its high melting point and recrystallisation temperature, was found to be unfavourable, but a little cold work greatly

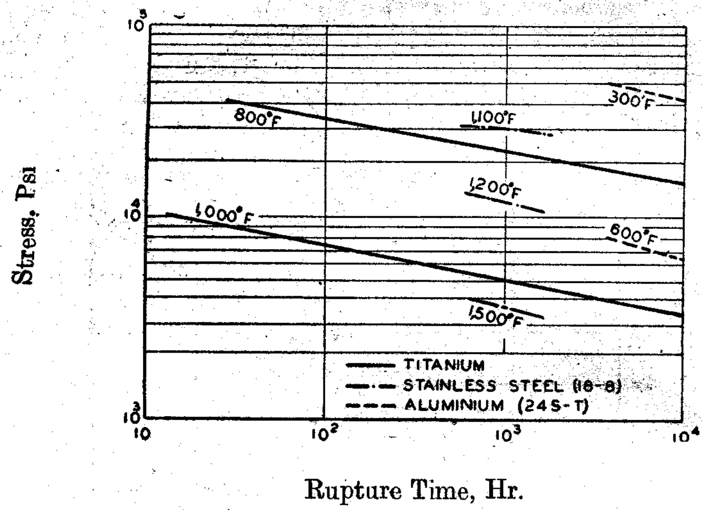

Fig. 3

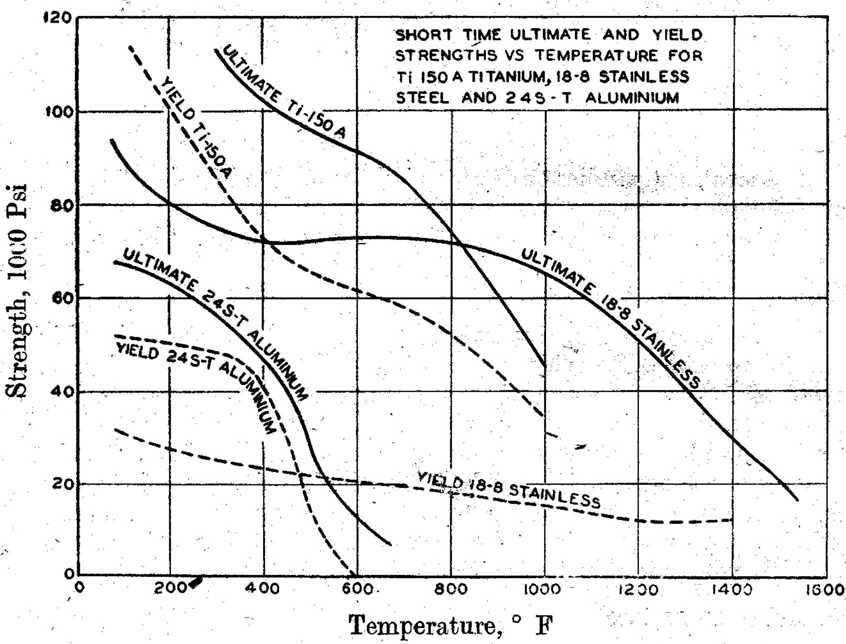

Fig. 3A

improves this characteristic of this commercially pure metal. The tests of forged titanium bar stock containing a maximum of 0·5 per cent carbon showed virtually little creep upto 600°F under the stress of 25,000 psi. However, a creep rate of 0·000015 per cent per hour was noticed at 800°F under the stress of 16,000 psi. Further tests on the same material indicate one hundred hours stress rupture value for titanium to be 32,000 psi at 800°F and 7400 psi at 1000°F. In figure No. 3 the stress rupture values of titanium have been compared with that of 24S-T aluminium alloy and 18-8 stainless steel. These values for titanium are far superior to 24S-T aluminium alloy in all respect.

Shear Strength

This property is particularly important as titanium may prove suitable for the aeroplane rivets and pins. Pins of 3/32 inches diameter from annealed hot rolled bar have an average shear strength of 82,000 psi, while similar tests on 75S-T aluminium alloy showed a shear strength of 42,000 psi only. There has always been a need for high strength rivet in the aircraft industry and for this reason it has attracted considerable interest as a possible and better substitute for the usual 24S-T aluminium rivet, particularly in highly stressed areas of aircraft frame and body. It has approximately 50 per cent greater ultimate shear value than 24S-T aluminium alloy.

Corrosion resistance

It is also an important property worth considering for the material which has to be in service in exposed atmospheric condition. The property of high resistance to corrosion decreases the cost of reconditioning and increases the life considerably. Aluminuim alloys (24S-T and 75S-T) which are used in aircraft construction are clad with a thin sheet of pure aluminium to resist corrosion. Titanium as such has got excellent corrosion resistance ; much better than even pure aluminium. Salt water tests show that its resistance to corrosion is better than stainless steel, monel metal etc. Samples of titanium immersed in sea for sixty days showed no trace of corrosion or loss in weight. Ordinarily, materials tested in this water show a marked lowering of the fatigue resistance caused by sharp notches formed by corrosion under the simultaneous application of cyclic stress. But in the case of titanium it was observed that the fatigue resistance was not at all inferior to that in air and thus it surpasses in this respect the very best structural alloys.

Ease of fabrication

Titanium can be easily machined, forged, drawn, welded and cold worked. Extrusion is also reported to be practicable.

Machinability

The machinability is somewhat difficult. Sturdy, rugged machines and tools capable of maintaining uniform, positive cutting feeds are necessary. It has a tendency to back away the cutting edge of the tool, hence sharp tools are essential, moreover a dull tool will work-harden or glaze the surface which will become very difficult to cut subsequently. Tungsten-carbide cutting tools are excellent for machining. They cut it with approximately the same speed and feed as 18·8 stainless steel. Cobalt base high chromium alloy tools can also be used. The depth of cut ranges from 1/32 inches to 3/32 inches. The most suitable speed of lathe is about 400 r.p.m.

Forgibility

It can be forged readily by the general conventional practice. A good forging characteristic is that the internal voids appear to weld rather than merely flatten. The regular heating furnaces may be used and no protective atmosphere need be employed. It works well between the temperature of 1500°F to 1600°F. Higher temperatures should not be used because a yellow oxide is formed which causes trouble. The finish forging temperature below 1525°F is important if good ductility of the metal is to be preserved. It has good flow characteristics, readily fills the die and gives clean, sharp die impressions. It has been, therefore, forged into a number of shapes *e.g.* turbine blades, rotors and large supersonic propeller blades etc.

Drawing property

It can be drawn into fine wires. The only precaution necessary is to pull the part out of the die while it is still hot, since its thermal coefficient of expansion is less than that of steel and it tends to freeze in the die if allowed to cool.

Weldability

It can be readily welded by the spot-welding methods, although other resistance welding methods including seam-welding, projection welding, flush and butt welding are also satisfactory. Electric arc welding gives excellent results provided an Argon shield electrode or heli-arc process is used to prevent contamination not only of the molten welded metal, but also all the heated parts of the base metal, including the back of the weld. In the welding operation the metal runs easily and there is no difficulty in producing sound ductile weld of good appearance.

Extrusion

It can be extruded as well because the problem that it wetted the matting surface and so had the tendency to weld to the extrusion die has been solved by using molten glass as lubricant.

Cold Working

Most of the parts which can be put to service are fabricated from the cold worked titanium. The properties are modified in a very interesting way as

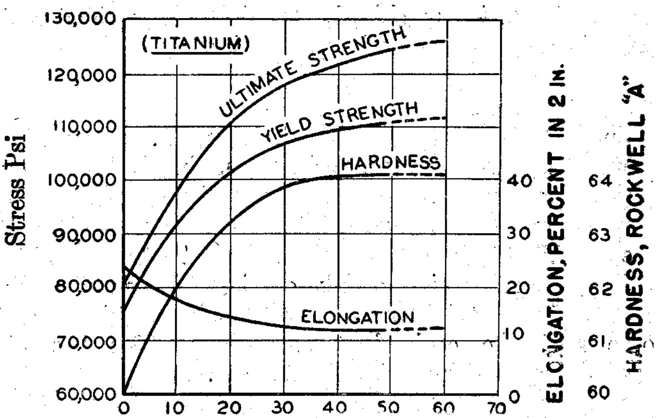

FIG. 4

can be seen from the figure No 4. The tensile properties are increased with a little decrease in ductility, so much so that at 50 per cent cold work when the ultimate tensile strength goes up to 125,000 psi the elongation percentage still remains at 12 to 15 per cent.

Availability

Titanium is available in abundance in nature. It is the fourth most plentiful structural metal in the earth's crust; exceeded only by aluminium, iron and magnesium. The important ores of titanium are ilmenite (FeO, TiO_2 having 32·33 per cent Ti) and Rutile (TiO_2 having 60 per cent Ti). The mineral ilmenite occurs as massive deposits in U. S. A., Canada and Norway and as beach sands in Travancore (India), Queensland and Florida. Rutile, which occurs to a lesser extent is found in Australia, U.S.A. and India. India has large deposits of this mineral and till the last war, she was the largest producer of this mineral, but her position has now been taken by U.S.A. Below are given the places in India where titanium is available in good quantities.

Place	Details
1. Travancore	Monazite sand contains 70 per cent ilmenite. It is the most abundant one in India.
2. Madras	In Trichinopoly district both ilmenite and rutile are found.
3. Bihar and Orissa	Extensive deposits of titani-ferrous iron ore are found in Singhbhum and Manbhum districts.
4. Rajputana	Deposits are reported in Alwar and Kishan Garh.
5. Punjab and U. P.	In Patiala State and Mirzapur districts ilmenite is found.

CONCLUSION

Titanium is a metal of modern age "with a future" and like aluminium, can come up in the front ranks of engineering and constructional materials if extended theoretical and practical investigations are carried out.

The greatest drawback for the economic industrial expansion of this metal appears to be the intricate and costly process of its manufacture which can be overcome only if some remarkable advances are made in the technique of its production by the metallurgists and engineers. India, especially, which has one of the largest deposits of the titanium bearing ores, is in a very advantageous position to utilise it industrially if only a process of cheap extraction of the metal can be developed.

At present much of the mineral titanium is being exported out and only a little of it is used in the manufacture of paints and pigments in our country. There is only one company in Travancore (India) which processes the mineral and a beginning has been made in the National Metallurgical Laboratory to produce the metal. There is a great need for an early production of the metal on a commmercial scale for industrial purposes.

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Figures 1, 2, 3 and 4 are from Product Engineering, Vol. 20, November 1949 and figures 1A and 3A are from Titanium Metal Corporation Hand Book.