The slope of the dilatometric curves for alloys containing 2-10% V is the same; the curves do not indicate any transformation inducing changes in the volume, since the ω-phase is formed only in alloys containing 12-18% V.

Quenched titanium alloys containing 2-10% Nb and Ta have the martensitic structure of the α'-phase. Their hardness increases with increasing concentrations of the alloying elements (Figs. 1 and 2). Annealing decreases the hardness of these alloys, apparently due to the relief of quenching stresses. The dilatometric curves for Ti–Nb and Ti–Ta are parallel, which indicates that their linear expansion coefficients are constant. There are no discontinuities on the curves, which indicates no changes in the volume resulting from phase transformations. In these alloys the ω-phase is formed at a higher concentration of the second component (22-30% Nb and 26-40% Ta).

CONCLUSIONS

1. We determined the phase composition and the hardness after quenching and after annealing between 20 and 600°C; we also determined the temperature ranges of the $\beta \rightarrow \omega$ and $\beta + \omega \rightarrow \beta + \alpha$-transformations in Ti–Fe, Ti–Cr, Ti–Co, and Ti–Mo alloys.

2. We determined the coefficients of linear expansion of these alloys between 20 and 900°C.

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IGNITION OF TITANIUM ALLOYS IN MEDIA CONTAINING OXYGEN

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An investigation of the ignition of titanium alloys in oxygen under pressure has led to the following hypothesis concerning the mechanism of this process: An exothermic oxidation reaction occurs on a surface of pure titanium in contact with oxygen, and this reaction leads to the formation of oxides with the evolution of a great amount of heat. When the oxidation rate is low, as in ordinary air, for example, the heat evolved in the reaction is dissipated and the temperature of the metal does not reach the temperature necessary for ignition. At higher oxidation rates (oxygen under pressure, for example) there is not enough time for the heat evolved in the reaction to be dissipated, and the metal begins to burn. Since titanium oxides are soluble in liquid titanium, and therefore do not prevent contact between titanium and oxygen, the reaction proceeds until all the titanium or oxygen is consumed. The following conditions must be satisfied for the reaction to occur:

1) The surface of the metal must be freshly cut (as in the case of the rupture of metals) and not covered with the usual oxide film.

2) The concentration of oxygen in the medium cannot be less than a certain critical value (not less than 35% in still air).

3) The oxygen pressure must also be above a certain critical value which depends on the composition of the medium.

The purposes of this investigation were as follows:

1) To determine the effect of the surface state on ignition.

2) To determine the effect of the temperature and the concentration of oxygen.

TABLE 1. Chemical Composition of Industrial Alloys and Critical Pressure Necessary for Ignition of Samples Ruptured at 20°C

Alloy	Chemical composition, average	Critical pressure, atm
Iodide titanium	—	75
BT1-1	—	20—25
BT3-1	5% Al; 2% Cr; 2% Mo	8
BT5	5% Al	9—12
BT5-1	5% Al; 2,5% Sn	9—12
OT4	3% Al; 1,5% Mn	10
OT4-2	6% Al: 1,5% Mn	7
BT6	5% Al; 4% V	8
BT8	7% Al; 4% Mo	13
BT10	5% Al; 2% Sn; 2% Cu	11
BT14	4% Al; 3% Mo; 1% V	13
BT15	3% Al; 7% Mo; 11% Cr	12

TABLE 2. Chemical Composition of Experimental Titanium Alloys and Critical Ignition Pressures of Samples Subjected to Tensile Strength Tests at 20°C in Oxygen

Chemical composition	Oxygen pressure, atm	Results	Chemical composition	Oxygen pressure, atm	Results
5% Al	15	Sample burned	30% Cr	40	Sample burned
10% Al	15	" "	15% Mo	50	" "
15% Al	20	Ruptured without igniting	30% Sn	75	" "
15% Al	25	" " "	30% V	50	" "
15% Al	30	Sample burned	30% Ni	30	Ruptured without igniting
20% Al	25	Ruptured without igniting	50% Ni	50	Ruptured and burned
20% Al	30	Sample burned	30% Mn	75	" " "
30% Al	50	Ruptured without igniting	5% Si	50	Sample burned
30% Al	95	" " "	10% Si	50	" "
30% Fe	50	Sample burned	30% Cu	75	Ruptured and burned

TABLE 3. Results of Elongation Tests without Rupture of the BT5-1 Alloy in Oxygen at Room Temperature

Applied load, kg	Oxygen pressure, atm	Results
1850	10	Samples ruptured without igniting
1700	12	Samples ruptured and burned
1580 (85% of $P_{rupture}$)	12	Sample did not rupture and did not ignite
1750 (94% of $P_{rupture}$)	12	Same
1750 (94% of $P_{rupture}$)	12	Same
1780 (95% of $P_{rupture}$)	50	Same
1680 (90% of $P_{rupture}$)	100	Same

Note: In all cases the samples were loaded for 3 min.

3) To determine the degree of inflammability of various industrial titanium alloys and the effect of alloying elements on resistance to ignition.

4) To test some methods of protecting titanium structures from igniting in media containing oxygen.

For these purposes we made tensile, compression, and bending tests in pure oxygen and media containing oxygen. For brittle rupture tests we used notched and nitrified samples, and to obtain two types of ruptures on the same sample we used surface hydrogenation.

The tests were made with an apparatus in which the samples could be subjected to stress independently of the oxygen pressure. A special instrument made it possible to remove shavings from the surface of the sample in media containing oxygen.

During the tests we determined the critical oxygen pressure, i.e., the pressure at which the sample ignites. The pressure was varied from 1 to 150 atm at temperatures up to 1000°C. We also varied the rate of application of stress.

The samples were made from industrial titanium alloys (BT1, OT4, BT3-1, BT5, BT5-1, BT6, BT8, BT14, BT15) and also from iodide titanium and some experimental alloys. The chemical composition of the alloys and the results of the experiments are given in Table 1.

Experiments showed that all alloys begin to burn in oxygen at room temperature when the samples rupture, provided the oxygen pressure is sufficiently high. The critical pressure varies from 8 to 75 atm, depending on the composition of the alloy. Iodide titanium required the highest critical pressure (70-75 atm). BT1 titanium ignites at a pressure of 20-25 atm, industrial alloys ignite at 8-15 atm, and experimental alloys (Table 2) ignite at 50 atm.

Alloying decreases the susceptibility to spontaneous ignition. For example, the alloy containing 5% Al ignites under a pressure of 10 atm, and with increasing concentrations of Al (up to 20%) the critical pressure increases to 25-30 atm. However, the highest amounts of alloyed elements used in practice (these amounts being limited by plasticity requirements) have almost no effect on the value of the critical pressure. It is increased significantly only when the amount of the alloyed element begins to induce brittleness. Only the alloy containing 30% Al remains stable in oxygen at a pressure of 100 atm. This alloy has an intermetallic base and its physical properties are different from the mass-produced industrial alloys. Thus, its conductivity (0.04 cal/cm • sec • deg) is equal to the conductivity of iodide titanium, while the conductivity of the other alloys is 0.02 cal/cm • sec • deg.

Fig. 1. Cracks along the boundaries of slip bands on the surface of sheet titanium subjected to tensile stress. ×10,000.

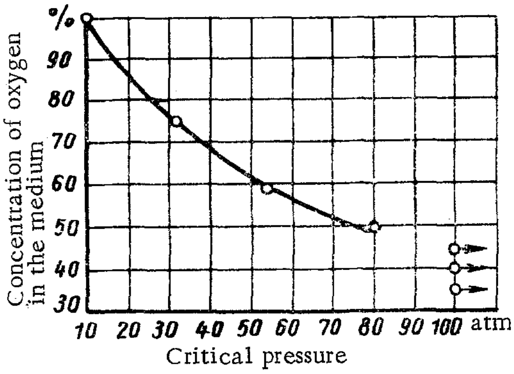

Fig. 2. Effect of the concentration of oxygen in the medium on the critical ignition pressure.

Preliminary investigations of the chemical composition of the oxide film showed that it contains not only TiO_2 but also Al_2O_3 and Al_2TiO_5.*

Titanium alloys ignite in oxygen under pressure only if there is a fresh fracture. Therefore, in practice titanium structures are never subjected to stress beyond the yield point.

Slip lines appear on samples subjected to elongation. These lines subsequently generate cracks leading to destruction (Fig. 1).

We investigated to what extent microcracks on the surface of the samples facilitate the ignition of the alloy. For this purpose, samples of the BT5-1 alloy were subjected to tensile stress but were not ruptured. The stresses created were close to the limit resistance to rupture. The samples were kept under this stress for 3 min in oxygen under pressures of 10, 50, and 100 atm, and then the pressure was decreased to atmospheric pressure. Table 3 shows that even highly deformed samples do not ignite under a pressure of 100 atm so long as they are not ruptured.

Thus, for titanium to ignite in a medium containing oxygen its surface must be free from the protective oxide film, i.e., titanium alloys can be used for parts working in still media containing oxygen provided the stress on the part is below the yield point.

We made the following experiments to determine the effect of temperature and oxygen concentration on ignition.

The media were different mixtures of nitrogen and oxygen. We found that the critical oxygen pressure for ruptured samples increases sharply with decreasing concentrations of oxygen (Fig. 2). The effect of temperature on the ignition pressure is given in Fig. 3. The pressure remains practically constant when the temperature is increased from 100 to 300°C, and the critical pressure decreases with further increase of the temperature. A freshly broken titanium sample at 900°C ignites in pure oxygen at atmospheric pressure. These data are in agreement with the known fact that titanium parts ignite when subjected to deformation at high temperatures. At 1000-1200°C titanium begins to burn at atmospheric pressure because the surface film is removed and a fresh surface is exposed if the part is dragged along the floor of the furnace. It must be noted that titanium samples do not ignite when the pressure is increased to 50 atm at a temperature of 950°C and a stress almost equal to the yield point. Under these conditions as well as at room temperature ignition occurs only if the surface has no oxide film. Since we did not succeed in developing an alloy resistant to oxygen under pressure, we tested different means of protecting alloys from direct contact with oxygen.

Structures made of titanium alloys may develop cracks at the points of stress concentration even when the average stress does not exceed the yield point. Therefore protective surface layers of metals which do not ignite in oxygen and are more plastic than titanium would prevent direct contact of a fresh crack with oxygen and thus decrease

* This investigation was made by I. A. Ponizovskaya.

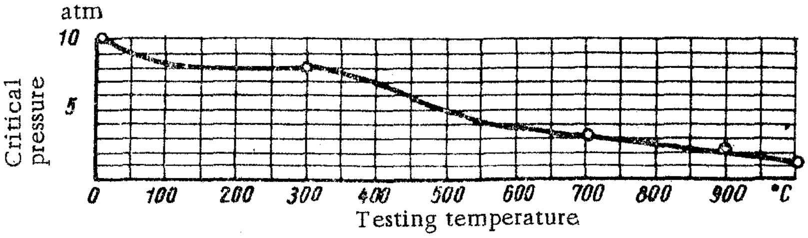

Fig. 3. Effect of testing temperature on the critical pressure of oxygen necessary to ignite the BT5-1 alloy in oxygen.

the probability of ignition. We investigated surface layers of copper, aluminum, and other neutral metals deposited electrolytically or by plating. Experiments showed that these surface layers do not protect titanium alloys from igniting if they are ruptured in oxygen, i.e., when the titanium surface has no oxide film. However, dense, pore-free coatings increase the dependability of titanium parts working under stress. Thus, tests of BT5-1 alloy showed that local ignition nuclei are formed when the pressure of oxygen is as low as 7 atm. The same alloy coated with a neutral metal withstands up to 20 atm without igniting.

CONCLUSIONS

1. Different titanium alloys ignite when ruptured in media containing oxygen under a pressure above a certain critical value. This critical oxygen pressure differs for each alloy.

2. Apparently it is impossible to create sheet titanium alloys with high plasticity which are resistant to oxygen under pressure. A titanium alloy with the intermetallic compound TiAl as a base which contains 30% Al does not ignite in oxygen under a pressure of 100 atm.

3. An increase of the temperature from 20 to 1000°C decreases the critical pressure of oxygen required for ignition. A decrease of the concentration of oxygen in the medium increases the critical pressure of oxygen.

A NEW ALLOY, BT15, WHICH CAN BE STRENGTHENED BY HEAT TREATMENT

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Titanium alloys with a β-structure can withstand short periods of exposure to higher temperatures better than any other titanium alloy. These alloys have a cubic lattice, which makes them plastic at room temperature. Because of this plasticity, the alloys are particularly useful as sheet material. The alloys containing the isothermally stable β-phase do not require heat treatment to improve their mechanical properties [1].

However, the alloys with an isothermally stable β-structure are less promising than the alloys with a "mechanically stable β-structure" i.e., alloys which can be strengthened by heat treatment.

When quenched, these alloys are more plastic and, after aging, stronger than the alloys with the isothermal β-structure.

At a given concentration of the β-stabilizer the alloy becomes self-quenching, i.e., will have a uniform plastic β-structure even when cooled from the β-region in air. Also, aging effectively strengthens these alloys.

The weldability of alloys with a mechanically stable β-structure is very good. Because of the self-quenching property of the alloy, the weld seams are plastic directly after welding, unlike those in two-phase alloys, which must be annealed after welding to restore the plasticity of the weld.

Alloys with a mechanically stable β-phase are becoming more important as the demand increases for stronger and more plastic materials.