Reports of the Academy of Sciences of the USSR

S. G. Fedotov, O. K. Belousov

1964

SovietRxiv

Abstract

Full Text

Reports of the Academy of Sciences of the USSR

1964. Volume 155, No. 6

Chemistry

S. G. Fedotov, O. K. Belousov

Elastic Properties of Multicomponent Alloys of Titanium with Molybdenum, Vanadium, and Niobium

(Presented by Academician I. I. Chernyaev, 25 XII 1963)

Elastic properties are sensitive characteristics of the phase structure of titanium alloys with transition elements ($^{1-3}$).

In work (^{2}), the concentration dependence of the change in the modulus of normal elasticity (E) and the shear modulus (G) was established for binary alloys of titanium with molybdenum, vanadium, and niobium in the annealed state and after quenching from the β-region.

We studied the conditions and mechanism of formation of metastable phases and established the regions of their occurrence in more complex systems, which can serve as a basis for the creation of new high-strength structural titanium alloys strengthened by thermomechanical treatment.

The alloys studied, of the systems Ti—Mo—V, Ti—Mo—Nb, Ti—V—Nb, and Ti—Mo—V—Nb, corresponding to sections with a ratio of alloying elements of $1:1$ in the case of ternary systems and $1:1:1$ for the quaternary system (wt. %), were melted in an arc furnace with a nonconsumable tungsten electrode in an argon atmosphere, using titanium sponge of grade TG-00 as the base.

The alloying elements—molybdenum, vanadium, and niobium—used for preparing the alloys were from the same batches as in works (^{2,3}). The heat treatment of ternary and quaternary alloys was carried out according to the same schedule as for alloys of binary systems (^{2}).

The obtained results of the study of the elastic constants of multicomponent alloys of these systems in the annealed state (at 600°) and after quenching (900°) are presented in Fig. 1 in comparison with the corresponding polythermal sections previously established in work (^{4}).

Fig. 1

Figure 1: Fig. 1

A comparative examination of the graphs presented in Fig. 1 shows that the investigated properties of the annealed alloys change qualitatively in the same way as a function of the composition and structure of the alloys for all systems, which is a consequence of the identical nature of the interaction of titanium with the indicated alloying elements, expressed by a single type of phase diagram.

These elements, introduced into titanium separately (^{2}) or together, lower the modulus of normal elasticity and the shear modulus of α-alloys and alloys of the $\alpha + \beta$-region. The transition to the single-phase region of β-solid solutions is marked by a minimum on the curves of elastic properties. Further alloying of homogeneous β-solid solutions leads to a monotonic increase in the properties.

The quantitative change in the elastic constants of titanium upon alloying is determined by at least three factors: the individual properties of the α- and β-modifications of titanium, the influence of alloying elements on the properties of these modifications, and the ratio of α- and β-phases in the alloy.

The data obtained for alloys in the annealed and especially in the quenched state make it possible to evaluate the contribution of individual factors to the overall change in elastic properties. First of all, from these data one may conclude that α-Ti has elastic properties at least twice as great as those of β-Ti, and that the indicated alloying elements exert an opposite influence on these properties of titanium in the α- and β-modifications. In the case of α-Ti they lower them, while in the case of the β-modification they increase them.

In order of decreasing effectiveness of action in binary systems, these elements may be arranged in the sequence: Mo $\rightarrow$ V $\rightarrow$ Nb, which, as is easy to note, corresponds to the sequence of their solubility in α-Ti. The less the alloying elements dissolve in α-Ti individually or in combination with others, the more intens—

the more intensively they reduce its elastic properties and, conversely, with greater solubility a smaller change in the elastic properties of α-Ti is observed. This regularity is most clearly manifested in quenched alloys.

Another feature consists in the fact, as was already noted earlier (^{2}), that in the change in the elastic properties of annealed alloys much is observed in common with the change in the temperature of the $\beta \rightleftarrows \alpha + \beta$ transformation. The temperature of phase transformations, like the elastic properties, decreases monotonically with an increase in the content of alloying additions in titanium.

Fig. 1. Concentration dependence of the modulus of normal elasticity (E), the shear modulus (G), and density (γ) of alloys of the systems:
a —Ti—Mo—V, —Ti—Mo—Nb, —Ti—V—Nb,
—Ti—Mo—V—Nb in the annealed (1) and quenched (2) states.

For alloys in the quenched state, a completely different character of the change in elastic constants has been found (see Fig. 1). It is very important that it is likewise unified, common to all systems, which reflects the commonality of the interaction of titanium with these elements also in multicomponent systems.

The difference consists only in the concentration extent of individual sections of the curves and in the intensity of the change in properties. The facts noted directly indicate that there is a direct connection between the individual elements of the metastable and equilibrium phase diagrams.

All alloying elements (molybdenum, vanadium, and niobium), when titanium is alloyed separately or jointly, at first intensively decrease the elastic constants of quenched alloys, then restore them almost abruptly to the initial or a higher value; after the maximum there is again a depression in the property curves, and then there follows a monotonic increase of them as the content of alloying elements in the alloys increases.

In the region of single-phase β-alloys, no appreciable difference is observed in the values of the elastic constants for the annealed and quenched states.

It was noted earlier (2) that the sharp decrease in the elastic constants of quenched alloys is connected with the formation of supersaturated α'- and α''-solid solutions; the ω-phase corresponds to the maximum on the elastic-property curves. The second minimum corresponds to the fixation of a metastable β-solid solution.

It may be stated with confidence that the character of the change in the elastic properties of alloys of multicomponent systems, identical with that in binary systems, is due to their analogous structure.

The continuous, monotonic decrease in the investigated properties of the alloys, characterized by the first section of the curves, is connected with an increase in the supersaturation of the α-solid solutions of titanium and, consequently, with an increase in the degree of distortion of the hexagonal crystal lattice. The retained β-phase, the amount of which increases with increasing content of alloying elements in the alloys, will also make some contribution to this decrease.

Molybdenum causes the most intense decrease in the elastic properties of quenched alloys (2). In decreasing order of intensity of action on the elastic constants, molybdenum is followed by vanadium and niobium. In alloys of more complex composition these elements cause an approximately additive change.

In quenched alloys the difference in the intensity of the decrease in the elastic constants is manifested especially clearly; this is connected with the different solubility of the alloying elements in α-Ti. Comparison of the compositions corresponding to the first minimum of the elastic properties with the limiting solubility of these elements in α-Ti in the equilibrium state convinces us that there is a direct dependence between these compositions. Greater solubility in α-Ti in the equilibrium state corresponds to a greater content of these elements in supersaturated solid solutions based on α-Ti.

Thus, the different magnitude of the solubility of the alloying elements in α-Ti determines the difference in the concentration extent of the first section of the elastic-property curves and the difference in the intensity of their decrease.

It is interesting to note that the magnitude of the elastic constants of the alloys corresponding to the first minimum is practically the same for all systems, i.e., it does not depend on the alloying elements and on whether they are introduced into titanium separately (^{2}) or jointly. This may indicate that, at the given compositions, the alloying elements cause identical changes in the hexagonal crystal lattice; that the distortion of the crystal lattice and, possibly, the ratio c/a due to supersaturation reaches the same and limiting value. The change in Poisson' s ratio with composition also supports such a conclusion. In the composition range under consideration its value increases, in connection with supersaturation, from 0.32 for titanium to the theoretically limiting value of 0.50, reached in alloys with the limiting concentration of alloying elements in practically all systems.

The limiting supersaturation compositions of alloys of different systems, as a result of ⋯

by their identical effect on the state of the crystal lattice of the alloys and on their properties, may therefore be called "equivalent."

It may be expected that the initial β-solid solutions corresponding to these compositions will be close in lattice parameter and in the temperatures of martensitic transformations.

All the facts considered lead us to the important conclusion that there is a limiting state of the crystal lattice which can apparently be reached not only by changing the composition, but also by the action of other factors of thermodynamic equilibrium—such as pressure and temperature. Within the range of states up to this limiting value, the crystal lattice permits various changes in connection with the action of different equilibrium factors (composition, temperature, and pressure); exceeding these factors leads to a loss of stability of the given lattice and to the formation of a new, more stable lattice state.

Consequently, one may now speak of limiting supersaturated solid solutions and of a limiting degree of supersaturation.

We believe that the so-called "critical" compositions for the formation of the ω-phase and for the retention of the metastable β-phase during quenching of alloys are also connected with the solubility of alloying elements in α-Ti.

In view of the fact that the curves of elastic properties in the first region show a continuous character of change with composition up to the maximum permissible supersaturation, it seems to us inadvisable to separate the α''-phase from supersaturated α-solid solutions as an independent phase. As regards the lower hardness of quenched alloys with a concentration of alloying elements close to the limiting one (according to Yu. A. Bagaryatskii—alloys with the structure of the α''-phase), in comparison with less-alloyed supersaturated solid solutions, this may be connected with at least three causes. First, with the very low bond strength of quenched alloys of these compositions (low moduli of elasticity); second, the martensitic $\beta \rightarrow \alpha$ transformations proceed at lower temperatures, in comparison with neighboring alloys less alloyed in composition, and therefore in these alloys the martensitic α-structure is to a lesser extent subjected to tempering in the course of the transformation, which, as is known, leads to strengthening of alloys; and the third cause lies in the lower hardness of the residual β-phase, the amount of which increases as the composition approaches the limiting concentration.

As a result of the investigation, a direct relation has been established between the solubility of molybdenum, vanadium, and niobium in α-titanium in the equilibrium state, when they are introduced into titanium separately or jointly, and the composition of their supersaturated solid solutions. The quantitative ratio of these compositions, equal in magnitude, expresses the limiting degree of supersaturation of the hexagonal crystal lattice of titanium by the indicated alloying elements.

The limiting degree of supersaturation is connected with the limiting elastic stability of the crystal lattice of α-titanium.

The character of the change in the elastic properties of titanium alloys with molybdenum, vanadium, and niobium, both in simple and in more complex systems, in the equilibrium state or after quenching, is in direct dependence on the chemical interaction of titanium with these elements, characterized by the phase diagram.

Institute of Metallurgy
named after A. A. Baikov

Received
23 XII 1963

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