Comparison of the Strength Properties of Heat-Resistant Titanium Alloys at Elevated Temperatures

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Abstract. The results of statistical studies of the strength properties of rods made of heat-resistant titanium alloys at test temperatures of 20–600 °C are represented. The initial data for the research were the results of experiments published in various sources from the 1960s to 2019. The chemical composition of the alloys has been compared by aluminum and molybdenum equivalents and tensile strength at various temperatures. With an increase in the degree of alloying with α-stabilizers and neutral hardeners, the heat-resistant properties of alloys increase and remain at higher temperatures. However, this may reduce the thermal stability of alloys with an aluminum equivalent of more than 9.0%. The highest strength properties while maintaining thermal stability have alloys with aluminum equivalents of 8.5–9.0% and molybdenum of 1.0–4.5%. Regression dependences of the average values of strength properties on the test temperature, silicon content, and aluminum and molybdenum equivalents of alloying elements and impurities have been determined.

1. Introduction

Currently, hundreds of experimental titanium compositions have been developed in the Russian Federation with more than 50 titanium alloy grades being used in industry for various purposes, of which about 10 alloys are designed for temperatures up to 600 °C [1, 2]. Heat-resistant alloys have been created mainly based on the α-phase with a small amount of β-phase (≤ 10 %), therefore, by the phase composition, they belong to the pseudo α- and α+β-classes. In Table 1, titanium alloys are arranged in the order of increasing the content of β-stabilizers.

The possibility of using titanium alloys at elevated temperatures can first be inferred by the dependence of short-term strength properties on temperature. For a theoretical evaluation of the tensile strength of α-, pseudo α- and α+β-titanium alloys of different classes at room temperature, the below equation can be used [3, 4]:

\[ \sigma_a = 380 + 65[Al]_{eq}^{\alpha} + 45[Mo]_{eq}^{\alpha} \]  \hspace{1cm} (1)

where \([Al]_{eq}^{\alpha}\) is the structural aluminum equivalent of α-stabilizers and neutral hardeners; \([Mo]_{eq}^{\beta}\) is the structural molybdenum equivalent of β-stabilizers [2]. However, for heat-resistant alloys, equation (1) should be adjusted since structural equivalents do not consider the effect of silicon, which is an
obligatory alloying component. This is due to the high lattice mismatch between silicon and titanium. These causes blocking of dislocations at sufficiently high temperatures and prevents their climb and cross gliding. The silicon content should be restricted by its solubility limit in the α phase since silicides do not lead to increase tensile strength depending on the test temperature and chemical composition expressed in aluminum equivalent.

Table 1. Nominal Composition and Operating Temperature of Heat-Resistant Titanium Alloys [2, 5–15].

| Alloy Class | Alloy  | Chemical Composition                  | Maximum Operating Temperature, °C |
|-------------|-------|---------------------------------------|----------------------------------|
| Pseudo α    | VT18U | Ti-6.5Al-2.5Sn-4Zr-1Nb-0.7Mo-0.15Si   | 550÷600                          |
| VT20        |       | Ti-6.5Al-1Mo-1V-2Zr-0.15Si           | 450÷500                          |
| VT41        |       | Ti-6.2Al-1.2Mo-4.0Sn-3.3Zr-1.2Nb-0.35Si-0.5W-0.1Fe | 550÷600                          |
| VT25        |       | Ti-6.5Al-1.5Sn-4Zr-2Mo-1W-0.15Si    | 500÷550                          |
| VT9         |       | Ti-6.5Al-3Mo-1.5Zr-0.25Si           | 500÷550                          |
| VT36        |       | Ti-6.2Al-2.1Sn-3.6Zr-0.7Mo-5.0W-0.15Si | 550÷600                       |
| VT8         |       | Ti-6.5Al-3.3Mo-0.3Si                | 450÷500                          |
| VT8-1       |       | Ti-6.5Al-3.5Mo-1.2Sn-1.2Zr-0.2Si   | 450÷500                          |
| α+β         | VT8M  | Ti-6.3Al-3.3Mo-1.0Sn-1.0Zr-0.15Si  | 450÷500                          |
| VT8M-1      |       | Ti-5.5Al-3.8Mo-1.2Sn-1.2Zr-0.18Si  | 400÷450                          |
| VT46        |       | Ti-6.0Al-2.0Mo-3Sn-0.8V-0.25Fe-2.5Zr-0.7Nb-0.2Si-0.05C-0.1O | 500÷550                          |
| VT25U       |       | Ti-6.5Al-1.8Sn-3.8Zr-4Mo-1W-0.2Si  | 500÷550                          |
| VT3-1       |       | Ti-6Al-2.5Mo-1.5Cr-0.5Fe-0.3Si    | 400÷450                          |

Aluminum equivalent \([\text{Al}]_{eq}^{\text{Al}}\) characterizes the thermal stability of alloys and is determined by the equation [2]:

\[
[\text{Al}]_{eq}^{\text{Al}} = %\text{Al} + %\text{Sn}/3 + %\text{Zr}/6 + 10\left[%\text{O} + %\text{C} + 2\%\text{N}\right]
\]  \(2\)

The thermal stability criterion is the plasticity of at least \(\delta = 10\%\) and \(\psi = 20\%\) preserved by the samples after they are exposed to a voltage of 246 MPa and a temperature of 540 °C [2]. Alloys lose thermal stability due to the release of the \(\alpha_2\)-phase (Ti₃Al) at \([\text{Al}]_{eq}^{\text{Al}} \geq 9\%\); therefore, the structural aluminum equivalent is sometimes called the thermal stability coefficient [5]. The molybdenum equivalent \([\text{Mo}]_{eq}^{\text{Mo}}\) characterizes the stability of the \(\beta\)-phase and is determined by equation [2]:

\[
[\text{Mo}]_{eq}^{\text{Mo}} = %\text{Mo} + %\text{Ta}/4.5 + %\text{Nb}/3.3 + %\text{W}/2 + %\text{V}/1.4 + %\text{Cr}/0.6 + %\text{Mn}/0.6 + %\text{Fe}/0.4 + %\text{Ni}/0.8
\]  \(3\)

Silicon is a \(\beta\)-stabilizer but does not affect the quantity and stability of the \(\beta\)-phase in commercial titanium alloys and therefore is not considered in formula (3).

The study objective was to compare heat-resistant titanium alloys based on an evaluation of the tensile strength depending on the test temperature and chemical composition expressed in aluminum and molybdenum equivalents and considering the silicon content.
2. Source Materials and Research Techniques
In the study, the results of experiments published in various sources from the 1960s to 2019 have been used as source materials. Generally, the VIAM study results published in papers, handbooks, and monographs have been used [5–15, 17–23]. The alloying degree of the alloys has been estimated using aluminum and molybdenum equivalents by the equation (2), (3). Statistical studies have been performed using the STATISTICA software package and included correlation-regression analysis with a confidence probability of 0.95 using standard techniques [16].

3. Research Results and Discussion
The chemical composition of heat-resistant alloys in aluminum and molybdenum equivalents is shown in Figure 1. A tendency towards a decrease in aluminum equivalent and an increase in molybdenum equivalent of alloying elements is observed. Figure 1 shows that the content of alloying elements for alloys operating at temperatures up to 400÷450 °C should not exceed $[\text{Mo}]_{eq}^{str} \approx 3.5 \div 6.5\%$ and $[\text{Al}]_{eq}^{str} \approx 7.0 \div 7.5\%$; up to 450÷500 °C – $[\text{Mo}]_{eq}^{str} \approx 1.5 \div 4.5\%$ and $[\text{Al}]_{eq}^{str} \approx 7.5 \div 8.5\%$; up to 500÷550 °C – $[\text{Mo}]_{eq}^{str} \approx 2.5 \div 4.5\%$ and $[\text{Al}]_{eq}^{str} \approx 8.5 \div 9.0\%$; up to 550÷600 °C – $[\text{Mo}]_{eq}^{str} \approx 1.0 \div 2.5\%$ and $[\text{Al}]_{eq}^{str} \approx 8.5 \div 9.0\%$.

The average equivalent values can be estimated to optimize the alloy composition by the ratio:

$$[\text{Al}]_{eq}^{str} = 9.53 \div 0.4 [\text{Mo}]_{eq}^{str}$$

(4)

VT18 and VT41 are considered the most heat-resistant alloys at temperatures of 550÷600 °C. However, in practice, VT18 alloy is not used due to low processability, and VT41 alloy is at the stage of industrial development [12]. The high strength properties of the latter are determined by multicomponent alloying, which leads to the formation of a carbide phase based on tungsten and additional hardening of the $\alpha$-solid solution with iron added in an amount within the solubility range [12, 15, 21, 22]. The most heat-resistant serial alloys are VT18U and VT25U [23].

![Figure 1. Chemical Composition of Heat-Resistant Titanium Alloys in the Coordinates $[\text{Al}]_{eq}^{str} - [\text{Mo}]_{eq}^{str}$.](image-url)
An analysis of the published literature shows that the strength and heat-resistant properties of titanium alloys strongly depend on the type of semi-finished product, the process modes of heat treatment, the type and parameters of the structure, and the grade composition fluctuations (Table 2).

**Table 2.** Mechanical Properties of Various Semi-Finished Products Made of Heat-Resistant Titanium Alloys.

| Alloy | Semi-Finished Product (Annealing) | Tensile Strength, MPa, at temperatures, °C | References |
|-------|-----------------------------------|--------------------------------------------|------------|
| VT18U | Rod 20 mm. Si = 0.1-0.12 %        | 935±1,010, 915±1,015, 910±1,100             | [17]       |
|       | Disk stamping                     | 600±700, 560±650                            | [15, 18]   |
|       | Forging up to 50 kg               | 550±600                                    | [19]       |
| VT46  | Rods                              | 1,170±1,250, 1,080±1,165                    | [13]       |
|       | Forging 15-25 kg                  | 770±850                                    | [23]       |
|       | Rods 45 mm                        | 1,030±1,180, 730±830                        | [12, 15, 18]|
|       | Forging up to 220 kg              | 730±830, 630±750                            | [19]       |
|       | Rods 18-22 mm. Fe = 0.06 %        | 1,010±1,035, 1,055±1,115                    | [21]       |
|       | Rods 18-22 mm. Fe = 0.12 %        | 1,145±1,190, 705±785                        | [22]       |
|       | Forging. Fe = 0.05-0.06 %         | 680±715                                    |            |
| VT41  | Forging. Fe = 0.11-0.12 %         | 675±725                                    |            |

E.g., the absolute properties dispersion of the same type of semi-finished products may reach 100÷150 MPa at both room and elevated temperatures (Table 2). Fluctuations in the iron content within the brand composition (0.06÷0.12 % m.) for the VT41 alloy lead to a divergence of $\Delta \sigma_s = 100÷180$ MPa. For some alloys, mechanical properties published in literary sources are extremely contradictory and require clarification. Therefore, at the first stage, the temperature dependences of the tensile strength of various semi-finished products (rods, sheets, forgings) after standard annealing have been analyzed based on an integration of the data published.

For the dependence of strength properties on temperature, the exponential law proposed by N.S. Kurnakov is usually applied [6]:

$$\sigma_u = \sigma_0 \cdot \exp(-bt)$$  \hspace{1cm} (5)

where $\sigma_0$ is the free term characterizing the strain resistance extrapolated to 0 K; $b$ is the temperature coefficient. For each alloy, a regression analysis has been performed using the exponential dependence (4) and a 3rd-degree polynomial (5):

$$\sigma_u = \sigma_0 + b_1t + b_2t^2 + b_3t^3$$  \hspace{1cm} (6)

Then, a comparison between actual and regression tensile strength values has been performed, which has shown that ratio (4) is valid only within a rather narrow temperature range of ~100÷400 °C. Within the studied temperature range of 20÷600 °C, for most alloys, a 3rd-degree polynomial gives the best approximation. The regression coefficients of the model (5) for rods made of various alloys, the statistical error $S$ of the tensile strength estimate, and the correlation coefficient $R$ are given in Table 3.

At the second stage, the dependence of the tensile strength of various semi-finished products on the aluminum and molybdenum equivalents and the silicon content (0.15÷0.35 %) at various temperatures has been analyzed (Table 4). At room temperature, an increase in the aluminum and molybdenum equivalents by 1.0 % leads to an increase in the tensile strength by an average of ~ 60 and ~ 50 MPa, respectively, which is comparable with relation (1). For silicon, the strength coefficient of 234 MPa/% m. is close to the literature data of 120÷300 MPa/% m. [2]. With increasing temperature, the effect of silicon on strength increases to 500÷600 MPa/% m. at 200÷500 °C. According to [17], for the VT18U...
alloy hardened with silicon, the strength coefficient values at room temperature and 600 °C are approximately the same and equal to 400–500 MPa/% m., while for the Ti-8-1-1 alloy, they are much different and equal to 150 MPa/% m. (at 20 °C) and 410 MPa/% m. (at 600 °C). From Table 4, it follows that alloys containing more α-stabilizers and neutral hardeners have higher strength properties, and the degree of their effect on strength is maintained up to 600 °C. With increasing temperature, the effect of β-stabilizers on the alloy strength decreases significantly, and at a temperature of 600 °C, the tensile strength increases on average by ~ 12 MPa with an increase in the molybdenum equivalent by 1.0 % m. (Table 4).

Table 3. Parameters of a 3rd Degree Polynomial Model (5) for Theoretical Evaluation of the Tensile Strength of Rods Made of Heat-Resistant Titanium Alloys within the Temperature Range of 20–600 °C.

| Alloy | \( [\text{Mo}]_{\text{eq}} \) | \( [\text{Al}]_{\text{eq}} \) | \( \sigma_0 \) | \( b_1 \) | \( b_2 \) | \( b_3 \) | R   | S, MPa |
|-------|----------------|----------------|----------|---------|---------|---------|-----|-------|
| VT18  | 0.9            | 10.5           | 1.135    | -1.256  | 0.0030  | 3.234·10^{-6} | 0.97| 53    |
| VT18U | 1.0            | 9.0            | 1.061    | -1.887  | 0.0045  | -4.155·10^{-6} | 0.93| 60    |
| VT20  | 1.7            | 7.8            | 1.088    | -3.345  | 0.0105  | -1.105·10^{-5} | 0.98| 34    |
| VT41  | 2.4            | 9.1            | 1.161    | -2.085  | 0.0061  | -6.664·10^{-6} | 0.98| 46    |
| VT25  | 2.5            | 8.7            | 1.121    | -0.789  | 0.0021  | -3.255·10^{-6} | 0.98| 50    |
| VT9   | 3.0            | 7.8            | 1.187    | -1.470  | 0.0034  | -3.881·10^{-6} | 0.99| 40    |
| VT36  | 3.2            | 8.5            | 1.102    | -0.920  | 0.0011  | 1.453·10^{-6}  | 0.99| 33    |
| VT8   | 3.3            | 7.5            | 1.129    | -1.329  | 0.0030  | -3.530·10^{-6} | 0.99| 33    |
| VT46  | 3.4            | 8.4            | 1.200    | -1.172  | 0.0029  | -4.012·10^{-6} | 0.99| 26    |
| VT25U | 4.5            | 8.8            | 1.190    | -1.501  | 0.0039  | -4.512·10^{-6} | 0.99| 49    |
| VT3-1 | 6.3            | 7.3            | 1.097    | -1.771  | 0.0045  | -5.251·10^{-6} | 0.99| 28    |

Table 4. Results of a Regression Analysis of the Dependence between the Tensile Strength of Rods and the Chemical Composition of Heat-Resistant Titanium Alloys at Various Temperatures.

| Test Temperature, °C | Regression Model                               | R   | S*  |
|----------------------|-------------------------------------------------|-----|-----|
| 20                   | \( \sigma_0 = 386+60[\text{Al}]_{\text{eq}} +50[\text{Mo}]_{\text{eq}} +234\text{Si} \) | 0.92| 56  |
| 100                  | \( \sigma_0 = 299+60[\text{Al}]_{\text{eq}} +45[\text{Mo}]_{\text{eq}} +369\text{Si} \) | 0.94| 58  |
| 200                  | \( \sigma_0 = 215+60[\text{Al}]_{\text{eq}} +45[\text{Mo}]_{\text{eq}} +497\text{Si} \) | 0.94| 57  |
| 300                  | \( \sigma_0 = 167+60[\text{Al}]_{\text{eq}} +40[\text{Mo}]_{\text{eq}} +590\text{Si} \) | 0.95| 60  |
| 400                  | \( \sigma_0 = 120+60[\text{Al}]_{\text{eq}} +40[\text{Mo}]_{\text{eq}} +495\text{Si} \) | 0.95| 51  |
| 500                  | \( \sigma_0 = 86+60[\text{Al}]_{\text{eq}} +40[\text{Mo}]_{\text{eq}} +475\text{Si} \) | 0.96| 48  |
| 600                  | \( \sigma_0 = 52+58[\text{Al}]_{\text{eq}} +12[\text{Mo}]_{\text{eq}} +372\text{Si} \) | 0.95| 45  |

Note: *S is the statistical error of the model.
Thus, with increasing the degree of alloying with α-stabilizers and neutral hardeners, the heat-resistant properties of alloys increase and remain at higher temperatures. However, it should be considered that the thermal stability of alloys with \([\text{Al}]_{\text{eq}} \geq 9\%\) may be simultaneously reduced.

4. Conclusions
1. A comparison of heat-resistant titanium alloys by chemical composition expressed in aluminum and molybdenum equivalents has been performed. This allows justifying the optimal composition of new alloys and evaluating their strength properties at various operating temperatures.
2. Based on statistical studies, mathematical dependencies of the most typical tensile strength values on the test temperature have been obtained for the rods made of heat-resistant titanium alloys.
3. Regression models have been determined to estimate (with a confidence probability of 0.95) the dependence of average values of the rod strength properties on the silicon content and aluminum and molybdenum equivalents of alloying elements at test temperatures of 20÷600 °C.

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