High-strength Titanium Bolts Processing for the Manufacture of Fasteners

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1. Introduction
Currently, an increase in the aircraft efficiency is achieved by reduction of its weight. The connection of various structural aircraft elements is carried out using a variety of fasteners (rivets, bolts, etc.). Fastening parts belong to one of the most important products of aviation and aerospace engineering in terms of mechanical and working properties requirements (they must have high weight strength, corrosion resistance, etc.). At the same time, fasteners are a typical example of mass-production products with multi-stage manufacture process, therefore, the materials for their manufacture must be technological enough at the forming stages, and have the possibility of subsequent strengthening to achieve high working properties.

High-strength titanium alloys, which satisfy the combination of the listed requirements, are one of the most common and promising materials for the fasteners manufacture [1-4]. Their chemical and phase composition, as well as structure should provide, on the one hand, the possibility of implementing economic technologies based on cold plastic deformation [3], and on the other hand, the achievement of a required level of mechanical properties of finished product after heat treatment. Taking into account these requirements, titanium alloys for the manufacture of fastening parts must belong to α+β-alloys with a sufficiently large amount of β-phase in the annealed state or to pseudo β-alloys [5-7]. For the production of relatively lightly loaded fasteners, the most successful combination of mechanical and technological properties is possessed by the VT16 α+β-alloy. Currently, it is the main industrial titanium alloy for the manufacture of fastening parts [8]. In a number of works [9-15], various ways to improve the mechanical properties of bolts from this alloy were investigated. At the same time, the development of aviation technology requires the use of fastening parts with higher working properties [3]. High-strength pseudo-β-titanium alloys is promising source material for important high-loaded fasteners manufacturing. Among Russian alloys, the most promising is the VT35 alloy that has high technological properties during room temperature processing [16]. Alloy VT35 is an analogue of the American Ti-15-3 alloy, but in addition to the main alloying elements (vanadium, chromium, aluminum and stannum), it contains small amounts of additional elements - molybdenum, niobium and zirconium. Early studies [9] on the VT16 alloy showed that their
introduction has a significant effect on the technological plasticity at room temperature. Therefore, in this work, studies were carried out on two bars of VT35 alloy with different amount of alloying elements.

At the present day, technologies of cold or hot reduction and upsetting are used for the manufacture of bolts from titanium alloys [1, 3]. Bolts with a diameter of up to 10 mm are cold-headed, while bolts with larger diameters are usually hot-headed, which reduces economic efficiency of their production. Therefore, the problem of producing bolts with a diameter of more than 10 mm with an increased mechanical properties by cold plastic deformation methods is urgent.

The deformability of titanium alloys is greatly influenced by the friction coefficient at the “metal-tool” interface. An increase in the coefficient of friction during hot and, especially, during cold deformation occurs due to the strong adhesive interaction of the surfaces of the deformable material and the tool. The adhesion of metal to the tool is caused by the formation of chemically clean surfaces and high chemical activity of titanium during processing. To improve deformability, it is necessary to reduce the coefficient of friction, which can be done by isolating the metal surface from the working surface of the tool with lubricants. In this case, lubricants must meet the following requirements [17]:

- Form a strong continuous film between the processed semi-finished product and the tool;
- Have a good adhesion to the surface of the semi-finished product;
- Retain its chemical properties over time;
- Must be easy to apply and remove.

In this work, the effect of various types of lubricants on the friction coefficient at the “metal-tool” interface is investigated in order to select the optimal lubricant for cold deformation of high-strength titanium alloys.

2. Materials and procedures
Investigations were performed on VT16 and VT35 alloy bars with a diameter of 16mm. Chemical composition of alloys are given in Table 1. Alloy VT35 of composition No. 1 contained all alloying elements according to the upper permissible limit (Ti-3Al-15V-1Mo-3Cr-3Sn-1Zr-0.4Nb). In composition No. 2, the amount of aluminum, vanadium, chromium and tin corresponded to the average GOST content, and the amount of molybdenum, zirconium and niobium corresponded to the minimum allowable.

| Alloy     | Main alloying elements*, (wt. %) | Mo<sub>eq</sub> |
|-----------|----------------------------------|---------------|
| VT16      | Al     2.8   V     4.2   Cr  3,67  Mo  1,82  Sn  3,83  Zr  1,74  Nb  0.35  19.4 |
| VT35      | Composition No. 1                |               |
|           | Al     3.9   V     15.9  Cr  1,82  Mo  1,82  Sn  3.83  Zr  0.35  Nb  19.4 |
| VT35      | Composition No. 2                |               |
|           | Al     2.9   V     14.9  Cr  0.55  Mo  2.82  Sn  0.53  Zr  0.02  Nb  15.1 |
| VT35      | Standard composition             |               |
|           | Al     2.4   V     14.0  Cr  2.4   Mo  0.5 - 2.0  Sn  2.4   Zr  0.5 - 2.0  Nb  0.01 - 0.4  13.8 – 20.2 |

* the rest is titanium

The chemical composition of the ingots was determined by X-ray fluorescence on a Professional Spectrum MEG-01 analyzer. Heat treatment was performed in air atmosphere using SNOL-2.2.5,18/10-I3 furnaces. Microstructures were investigated using a Cals Zeiss Axio-Observer.A1m graphic microscope at up to x1000 magnification. Light-field mode in air atmosphere was used.
analysis of the obtained images was carried out using the ImageExpert Pro 3 software package. Rockwell hardness was measured on a MacroMet 5100T device in accordance with GOST 9013-59. Mechanical properties at room temperature were determined using Tiratest-2300 testing machine with specialized grippers. Tensile, compressing and shear mechanical tests were carried out in accordance with GOST 1497-84, GOST 8817-82 and OST 1.90148-74, respectively. The oils of the "Molibden benzin mannol Teilsynthetic MoS₂" brands; colloidal carbon solutions of different densities; an aqueous solution of molybdenum disulfide, a soap solution and a solution of oxalic acid (so-called oxalating) were chosen as lubricants.

3. Results and discussion

The technological scheme for the manufacture of bars with a diameter of 16 mm included β-area forging and subsequent (α+β)-region rolling. Structures of all deformed semi-finished products were typical for alloys of the corresponding classes. Thus, VT16 alloy rolled bar structure is represented by the α- and β-phases, moreover, there are primary globular α-particles, which are retained in the structure during deformation in the (α+β)-region, and secondary lamellar α-particles, which are formed during β→α-transformation after cooling to room temperature. The structure of bars made of VT35 alloy after hot deformation is represented by β-phase grains and a very small amount of globular α-particles (Figure 1).

![Figure 1. VT16 (a) and VT35 (b) titanium alloys bars structure after forging and rolling.](image)

To carry out cold deformation, titanium bars must have the ability to deform during compression to a degree of more than 65% without cracking (GOST 8817-82). Since the bars are in a mechanical hardened state after rolling, additional annealing was carried out to increase their plasticity before further processing. Bars made of VT16 alloy were subjected to simple and stepwise annealing. VT35 alloy bars were heated to a temperature of 800°C, corresponding to the β-region, and cooled in air, which provides enough cooling speed for quench hardening of this alloy, due to the high content of β-phase stabilizing elements. The two-phase (α+β)-structure of VT16 alloy after annealing in two modes differed in the size of the α-phase particles (Figure 2 a, b). Quenching of the VT35 alloy bars from the β-area temperature leads to the formation of a single-phase β-structure (Figure 2, c, d).

To assess the technological plasticity at room temperature, samples were cut from the bars to determine the ultimate compression ratio. The tests were completed when the maximum possible force developed by the testing device was reached or interrupted when cracks appeared on the lateral surface of the sample. When testing the VT16 alloy, the limiting degree of samples compression was 60% after 730°C annealing and 80% after stepwise annealing. The increase in plasticity after stepwise annealing is associated with a slight increase in the structural components size and a decrease in the dislocation density.
The compressing of hardened VT35 alloy samples of different chemical composition showed that the limiting compression ratio of “Composition No.1” samples, alloyed to the upper limit, was 32%, while it was 78% for “Composition No.2” samples. It should be noted that the compressing of the VT35 alloy “Composition No.1” samples occurs with the appearance of cracks. This is due to its strong solid solution strengthening by alloying elements. Thus, the studies carried out have shown that to ensure high technological plasticity, the VT35 alloy should contain no more than 3% aluminum and the minimum possible amount of additional elements - molybdenum, zirconium and niobium.

The study of lubricants influence on the friction coefficient at the “metal-tool” interface was carried out on VT16 alloy bars. At the first stage of the work, the wettability of samples surface by considered lubricants depends on the surface preparation type. The contact angle was determined, i.e. the angle that a solution drop forms on the flat surface of the samples. The larger this angle, the higher the wettability (Figure 3).

Studies have shown that the better the degreased and well-developed surface of the sample, the greater the contact angle for the soap solution (Table 2). At the same time, with minimal surface preparation, the oil “Molibden benzin Mannol” and oleic acid are well adsorbed by the metal surface: the drop instantly spreads over the surface and almost 100% wettability takes place.

It was found that the contact angle for colloidal-carbon solutions depends on their specific surface area: the larger it is, the higher the contact angle. Also, it was shown that an increase of molybdenum disulfide (MoS₂) amount in solutions leads to a slight increase in the contact angle.
Table 2. Contact angle of liquid lubricant.

| Lubricant type               | Determining factor          | Contact angle |
|------------------------------|----------------------------|---------------|
| Soap solution                | Without preparation        | 32°           |
|                              | Grinding + polishing       | 19°           |
|                              | Oxalation                  | 11°           |
| "Molibden benzin Mannol" oil | Grinding + polishing       | 180°          |
| Oleic acid                   | Grinding + polishing       | 180°          |
| Colloidal carbon solution    |                            |               |
| 1260 m²/g                    |                            | 138°          |
| 1580 m²/g                    |                            | 148°          |
| 2130 m²/g                    |                            | 153°          |

At the next stage of work, the relative friction coefficient at the “metal-tool” interface was determined. The experiment was carried out in a specially made tooling. Samples with lubricant applied to their surface were pressed inside with the same force.

The technological tests carried out showed that the use of liquid lubricants (oil, oleic acid, colloidal carbon, soap solutions) for deformation is impractical, because the friction coefficient increases tens of times and the metal sticks to the tool (Table 3). Interesting results were obtained using oleic acid with molybdenum disulfide as a lubricant. If the lubricant was applied immediately before the tests, then the values of the extrusion stress and the coefficient friction turned out to be 2.5 times higher than after testing the samples to which the lubricant had been applied in advance (Table 3). Thus, when compressing, liquid lubricants do not fulfill their main function of reducing the friction coefficient.

Table 3. Extrusion stress and relative friction coefficient at the metal-tool interface, depending on the lubricant.

| No. | Lubricant                                           | Extrusion stress, MPa | Friction coefficient |
|-----|----------------------------------------------------|-----------------------|----------------------|
| 1   | Soapy solution after drying                        | 20,0                  | 1,8                  |
| 2   | Oxalation with saponification                      | 11,0                  | 1,0                  |
| 3   | "Molibden benzin mannol Teilsynthetic MoS₂" oil   | 125                   | 11,4                 |
| 4   | Colloidal carbon aqueous solution (specific surface area 2130 m²/ g) | 85                    | 7,7                  |
| 5   | Oleic acid                                         | 40                    | 3,6                  |
| 6   | Oleic acid + 50% MoS₂ (tested immediately after application) | 63                    | 57                   |
|     | Oleic acid + 50% MoS₂ (tested 72 hours after application) | 33                    | 3                    |

The best lubricating properties were shown by the saponified oxalate coating. It provides minimal extrusion force. In addition, it should be noted that the coating deforms together with the base metal, does not crack and does not slip.

The use of an aqueous soap solution as a lubricant applied directly to the surface of the sample without preliminary oxalation also showed good results, but at the same time the extrusion force and, accordingly, the friction coefficient increase by 2 times.

High compression ratio is a necessary condition for semi-finished products intended for cold compression. The strength of the investigated alloys during compression does not exceed 800 MPa.
However, the finished fastening parts must have a regulated tensile strength (not less than 950 MPa for VT16 and 1050 MPa for VT35) and a shear strength of more than 650 MPa [18, 19].

Therefore, after the bolt heads upsetting, it is necessary to carry out their hardening heat treatment. The work [20] describes the regularities of the structure formation in the VT35 alloy during heat treatment. Based on the available data, the aging of the VT16 and VT35 (Composition No.2) samples was carried out at temperatures of 450 °C and 475 °C, respectively.

Metallographic studies have shown that after aging, a typical structure is formed for each alloy, represented by dispersed α-particles and β-grains (Figure 4).

Tensile and shear tests have shown that low-temperature aging provides studied alloys bars with the required values of strength, relative elongation and shear stress (Table 4).

![Figure 4. VT16 (a) and VT35 (b) samples structure after hardening heat treatment:
(a) VT16: aging at 450°C, 15 hours holding;
(b) VT35 (Composition No.2): aging at 475°C, 30 hours holding](image)

| Table 4. Mechanical properties of VT16 and VT35 alloys samples after the hardening heat treatment. |
|---|---|---|---|---|---|
| Alloy | Heat treatment mode | HRC | $\sigma_b$, MPa | $\delta$, % | $\psi$, % | $\tau$, MPa |
| VT16 | Step annealing + Aging | 38 | 1010 | 17 | 62 | 670 |
| VT35 (Composition No. 2) | Quench hardening + Aging | 44 | 1360 | 7 | 15 | 810 |

4. Conclusions

Based on the research a heat treatment technology was proposed in the manufacture of fastening parts from VT16 and VT35 alloys with a diameter of 16 mm using cold heading.

To ensure high technological plasticity, the VT35 alloy should contain no more than 3% aluminum, the content of the main β-stabilizers and stannum should not exceed the average value, and the content of molybdenum, zirconium and niobium should be closer to the lower limit.

It was shown that preliminary annealing should be carried out before the compression: stepwise annealing should be used for VT16 alloy, while air cooling from the β-region should be used for VT35 alloy. During the upsetting process, it is recommended to use an oxalate coating with saponification as a lubricant. In order to achieve the required performance properties of the cold-produced bolts, subsequent aging should be carried out at temperatures of 450°C for VT16 alloy and 475°C for VT35 alloy.

5. References

[1] Bratuhin V and Vasiliev V 2010 NNSTU n.a. R.E. Alekseev works 1(80) pp 210 - 15
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