The correlation among chemical composition, structure and mechanical properties in titanium alloys for the elements with increased dynamic ability

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Abstract This article contains the comparison of physical and mechanical properties of several titanium alloys. The chemical composition influence on mechanical properties is investigated. VT22I and VT35 highly alloyed titanium alloys are the most prominent materials for armor elements production with ultimate tensile strength of 1200-1400 MPa and impact strength of 0,25-0,3 MJ/m².

1. Introduction
Contemporary armored cars have special requirements for its armor elements placement. Armor elements must fully protect automobile’s interiors to prevent passengers and car’s engine from damaging. It includes the windshield, car’s bottom and dashboard space. Armor plates also must provide overlap protection of vehicle’s doors and windows. In other words, the main goal is to provide all-around protection (Fig. 1). Aluminum alloys (AMg5, V95, 1901, etc.) and steels (77, 44S, C85, SPS43, etc.) are the main metallic materials used for armor production [1, 2]. Light armor (class 1 and 2) are usually made of medium-strength heat-treated aluminum alloys, while medium-carbon medium-alloyed steels are used for more durable armor. As for class 3, 4 & 5 armored vehicles, it is also important to have a high-level specific weight [3]. Usage of 6-8mm-thick steel armor plates are greatly increasing the weight of vehicle and decreasing controllability.

Figure 1. Class 5 armoring scheme of Lexus LS 600

Regardless of required armoring class, its goal is to create a safety place for passengers, which provides bullet and explosive fragments protection. It is vital to understand that although car weight is drastically increasing after armoring, it still must be safe to use it alongside with other movement...
participants on public roads. That is only achievable by using off-road trucks or car with frame chassis. Because of that, weight-reduction of these vehicles and maintaining its technological and service abilities is high-priority task.

One of the way to solve this problem is to use titanium alloys, which have a unique combination of physical, mechanical and chemical properties, and 40% lighter than traditional steels used for armor elements. There are hundreds of industrially manufactured titanium alloys, produced in Russia, as well as all over the world [4]. Because of that, it is more important to choose one of the existing alloys with increased dynamic ability than to develop a new one. Titanium alloys have been already successfully used in body armor (Table 1), so many hot deformation schemes are known to produce high-quality sheets as well as finished products [5-7].

Unlike body armor (such as bulletproof vests and helmets), armored vehicles plates (such as plates for armored cars) are larger and should have good shape repeatability during production cycle. At the same time, finished products must have high level of static and dynamic strength. For this reason, cold deformation should be used for their production.

| Table 1. Chemical composition and weight of metallic materials used in body armor. |
|-----------------|-------------------------------|----------------|-----------------|
| Alloy           | Chemical composition         | Weight strenght, km | Finished product / Maximum armor class |
| SPS-43          | 0,43C-1,63Si-1,2Cr-1,3Ni-0,45Mo | 255 – 260         | Bulletproof vest «Module 3M» / Class III |
| VT6             | Ti-6Al-4V                     | 200 – 245         | Armored helmet K6-3 / Class II |
| VT14            | Ti-4,5Al-1V-3Mo               | 245 – 265         | Bulletproof vest 6B2 / Class II |
| VT23            | Ti-5,5Al-4,5V-2Mo-1Cr-0,6Fe   | 215 – 275         | Bulletproof vest «Visit-M» / Class II, 6B5 / Class II |

Because of that, titanium alloys used for armor production must combine good technological properties with heat hardening ability. That is achievable by controlling the aluminum concentration in the alloy. On one hand, it must be high enough to provide α-phase solid solution hardening, but on another hand, it should not drastically decrease workability, especially during cold deformation procession [8]. It is known, that the best technological properties during cold deformation process are achieved if the alloy has about 3% of aluminum. As noted in article [9], VST2 titanium alloy (similar to VT6 alloy, which produced by recycling technology) will have the best ballistic properties if its mechanical properties are about 1250-1300MPa of ultimate tensile strength and about 18% of elongation. However the best correlation can be determined between material ballistic properties and its impact strength [9]. Thereby, the analysis shows, that high-alloyed transition and near-β-titanium alloys are the most prominent materials, which can be used for manufacturing of products with increased dynamic ability. The main goal of this work is to investigate the influence of chemical composition and structure on mechanical properties of such titanium alloys.

2. Materials and procedures
Investigations were performed for the 8-12 mm thick industrial manufactured sheets made of titanium alloys. The chemical composition of these alloys are presented in Table 2.

Heat treatment was performed using SNOL-2.2.5.1,8/10-I3. The microstructure was investigated in a light-field mode using a Cals Zeiss Axio-Observer.A1m graphic microscope with the help of ImageExpert Pro 3 image analysis system. Hardness was measured according to GOST 9013-59 using the BUEHLER Macromet 5100T device. The mechanical properties under tension and impact were determined according to GOST 1497-84 and 9454-78 using Tiratest-2300 testing machine and impact pendulum-type testing machine PSV-30.
### Table 2. Investigated titanium alloys chemical composition.

| Element | Basic alloying elements*, (wt. %) | MoE |
|---------|----------------------------------|-----|
|         | Al  | V   | Cr   | Mo | Sn | Zr | Nb | Fe |
| VT16    | 2,8 | 4,3 | –    | 5,1| –  | –  | –  | –  |
| VT22I   | 3,1 | 4,8 | 1,2  | 5,3| –  | –  | –  | 0,9|
| VT35    | 2,9 | 14,9| 2,4  | 0,6| 2,8| 0,5| 0,02| –  |

* except titanium

3. Results and discussion

The structure of semi-fabricated products in the deformed was investigated. VT16 and VT22I sheets rolling was held at high \((\alpha+\beta)\)-area temperatures, while VT35 sheets were rolled at \(\beta\)-area temperatures. Both alloys were cooled on air. It was revealed that structure of VT16 and VT22I sheets is well-worked and presented by lamellar \(\alpha\)-particles, as well as by \(\beta\)-phase (Fig. 2 a,b). The structure of VT35 sheets is monophase because of \(\beta\)-phase stabilizing elements high ratio and consists of deformed \(\beta\)-grains (Fig. 2c).

![Figure 2](image_url)

**Figure 2.** VT16 (a), VT 22I (b) and VT35 (c) sheets structure in hot rolled state.

Mechanical properties were estimated by hardness measurements of all investigated sheets. It was shown in table 4 that increased ratio of \(\beta\)-phase stabilizing elements provides VT22I hardness boost compared to VT16, because of more dispersed structure formation. Despite of even higher molybdenum equivalent of VT35 alloy, its hardness are much lower than the hardness of other two alloys, due to the absence of \(\alpha\)-phase.

### Table 3. Titanium alloys sheets hardness in worked and strengthened heat-treated state.

| Alloy   | Molybdenum equivalent | Hardness, HRC |
|---------|-----------------------|---------------|
|         |                       | worked stated | after strengthening heat-treatment |
| VT16    | 8,2                   | 31            | 38            |
| VT22I   | 12,9                  | 38            | 42            |
| VT35    | 15,1                  | 25            | 44            |
The influence of heat-treatment on structure formation and mechanical properties was also investigated. All of semi-fabricated products were strengthened by heat-treatment, which consists of high-temperature annealing and subsequent aging. The annealing of VT16 and VT22I was held at (α+β)-area temperatures, while heating of VT35 was held at temperatures slightly higher than polymorphic transition temperature. To prevent contraction processes all sheets was air cooled. VT35 heat-treatment can be classified as quenching, due to high concentration of β-phase stabilizing elements in this alloy, which prevents $\beta \rightarrow \alpha$-transformation during cooling.

Sheets aging treatment was held at 450$^\circ$ – 475$^\circ$C temperatures for 15-25 hours. At was revealed that microstructure of all titanium alloys after strengthening heat-treatment presented by dispersed particles as well as β-phase (Fig. 3). This kind of structure provides hardness boost of all investigated alloys (Table 3).

![Image](image_url)  
(a) VT16: 790°C, 1 hour, air cooling + 450°C, 15 hours, air cooling  
(b) VT22I: 770°C, 1 hour, air cooling + 450°C, 20 hours, air cooling  
(c) VT35: 800°C, 1 hour, air cooling + 475°C, 25 hours, air cooling

Figure 3 – Sheets structure after strengthening heat-treatment:

- a. VT16: 790°C, 1 hour, air cooling + 450°C, 15 hours, air cooling
- b. VT22I: 770°C, 1 hour, air cooling + 450°C, 20 hours, air cooling
- c. VT35: 800°C, 1 hour, air cooling + 475°C, 25 hours, air cooling

Mechanical properties of all sheets were measured in strengthened heat-treated state. It was shown that levels of ultimate tensile strength, as well as elongation and bottling of VT22I and VT35 alloys are satisfy the requirements, which was calculated for armored vehicles production. It was also revealed that VT16 sheets have a much lower ultimate tensile strength, which is insufficient for required dynamic ability (Table 4). Hence its usage as high-class armor elements production are not recommended.

| Allow  | Heat-treatment scheme | $\sigma$, MPa | $\delta$, % | $\psi$, % | KCU, MJ/m$^2$ |
|--------|-----------------------|--------------|-------------|-----------|----------------|
| VT16   | 790°C, 1 hour, air cooling + 450°C, 15 hours, air cooling | 1070 | 15 | 53 | 0,45 |
| VT22I  | 770°C, 1 hour, air cooling + 450°C, 20 hours, air cooling | 1190 | 7 | 15 | 0,35 |
| VT35   | 800°C, 1 hour, air cooling + 475°C, 25 hours, air cooling | 1380 | 6 | 13 | 0,23 |

4. Conclusions

It was investigated that the most prominent titanium alloys that can be used to manufacture class 5 or higher armored vehicles are VT22I and VT35 highly alloyed titanium alloys. It was revealed, that morphology and size of alloy structure could be adjusted in large margin using different schemes of heat-treatment, which is a vital factor to obtain a great combination of technological and services
properties. Armor products made of such titanium alloys could be produced using cold deformation process, while maintaining ultimate tension strength of 1200-1400 MPa and impact strength of 0.25-0.3 MJ/m².

5. References
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