# Investigation of Properties of Titanium Alloys with Mechanically Stable Beta-Structure for Body Armor Application

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Systematic research of protective performance of titanium alloys has been conducted in NII STALI since 1958 in order to evaluate the potentials of their application as materials which provide reliable operation of components and assembly units of transport facilities and special-purpose vehicles under intense impact loading. The properties of actually all existing structural titanium alloys with different structure types were investigated both as a mono-material and in compound structures or in combination with high-strength steels, aluminium alloys, ceramics and high-modulus polymers. The conclusion has been made that for different titanium alloy applications the requirements concerning physical, mechanical and technological performance can vary to a great extent, but what remains invariable is the requirement of using alloys with highest possible hardness (which also means highest possible strength) with maintaining or increasing ductility and reserve toughness of alloys at ambient temperatures.

It has been stated that for relatively simple-shape armor components exposed to impact loading most efficient alloys are VT6 and VT23. These alloys with $\alpha+\beta$ - structure are used mainly in annealed state which provides optimal combination of strength characteristics ($\sigma_B$ about 900-1200 MPa) and toughness (about 40-60 J/cm$^2$). Multiple experiments have revealed inexpediency of volume heat hardening of titanium alloy components with tempering and aging, as it results in lower endurance and drastically low survivability (formation of brittle fractures and back spalls) of the components. At the same time, use of speeding electrothermic surface treatment with varying-hardness structure formation throughout the component depth resulted in considerable positive effect on components made of VT23 alloy.

Complex-shaped components made by deep cold stamping nowadays are produced of low-strength ($\sigma_B$~600-700 MPa) high-ductile "pseudo-$\alpha$-alloys" grades OT4-1 or PT3-V. Because of higher requirements to endurance and weight characteristics of complex-shaped components there's a problem of selection or development of a titanium alloy with high technological ductility which would reduce the component weight by 15-20% due to better strength characteristics.

To solve the problem we think it expedient to investigate titanium alloys with meta-stable $\beta$ - structure, or so called "pseudo- $\beta$ - alloys".

To "pseudo- $\beta$ - alloys" class belong titanium high alloys with $\beta$- stabilizing elements ($K_\beta$ =1.6-2.8). Because of high stability the structure of $\beta$ - phase of these alloys is retained not only after tempering but also after annealing at temperatures higher than $\alpha+\beta \leftrightarrow \beta$ - transformation and subsequent cooling in air in cross-sections up to 100mm. Meta-stable $\beta$ - phase in the alloys of this class is mechanically stable, i.e. does not disintegrate in the process of plastic deformation and changes only at heating. A specific feature of $\beta$- alloys processed for the solid solution is a small difference between ultimate strength and yield strength values and a very low uniform elongation value. However, it does not mean (as one could think) that $\beta$- alloys feature little strain hardening. As it can be seen from comparison of true tensile stress - deformation diagrams of titanium alloys with different structure types, $\beta$ - alloys feature significant hardening even at the stage of concentrated deformation. It results in formation of a wide zone of concentrated deformation along the sample length. Even after neck formation, as loading further increases, deformation takes place not only in the neck but also in adjacent zones; as a result $\beta$ - alloys with minimal content of additions acquire high characteristics of ductility, toughness and straining ability at different types of loading which are close to those of unalloyed titanium. Alloys with $\beta$ - structure can effectively harden after tempering and aging, though to achieve such hardening some technological restrictions are to overcome; such restrictions are caused by irregular decomposition of solid solution which results in embrittlement of the material if the half-finished product has coarse-grained structure. The following alloys belong to the group of alloys with pseudo-β-structure with mechanically stable β- phase: B-120VCA (USA), VT15, TS6 etc.

Titanium alloys with mechanically stable β-phase feature the following disadvantages:

- higher density and price as compared to other titanium alloys because of considerable number of alloying elements;
- sensitivity to effect of interstitial impurities. Higher content of interstitial impurities (O, N, C) introduced with burden materials can result (as typical for other metals with volume-centered lattice) in drastic drop of operational temperature.

Almost all alloys of this type are experimental or small-scale production ones.

The present paper discusses the results of investigation of alloys with Kb>2,0 containing Al, Cr, Mo, V, Zr and Fe. The composition of experimental alloys is presented in Table 1.

Ingots of the experimental alloys were subjected to plastic deformation in order to obtain half-finished products in the form of sheets and plates.

The subjects of investigation were mechanical properties of the alloys at static and dynamic loading, technological characteristics of sheet stock and ballistic resistance of the material.

Tensile properties of experimental alloys were determined according to GOST 1497-84 standard on quintuple samples Type II No.6. Impact bending test was arranged according to GOST 9454-78 standard on samples Type 1.

Effect of hardening temperature on mechanical properties of one of the experimental alloys is shown in Fig.1. The test results have revealed that impact strength is most sensitive to hardening temperature. The tests of other alloys yielded the same results. Optimal hardening temperature range for the investigated compositions was 850-950°C which corresponded to formation of one-phase polyhedral structure of β- solid solution in the experimental alloys.

*Table 1 The composition of experimental alloys*

| Alloy Designation | Chemical composition of alloy, mass % | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Al | Cr | V | Mo | Zr | Fe | $O_2$ | $N_2$ | $H_2$ |
| 415 | 3.00 | 10.20 | - | 7.80 | 0.62 | 0.32 | 0.03 | 0.04 | 0.004 |
| 421 | 2.95 | 10.30 | 9.90 | 2.80 | 1.60 | 0.25 | 0.02 | 0.03 | 0.001 |
| 462 | 2.87 | 15.94 | - | - | 1.93 | 0.30 | 0.02 | 0.05 | 0.001 |
| 464 | 2.87 | 16.89 | - | - | - | 0.30 | 0.05 | 0.05 | 0.002 |
| 466 | 2.83 | 15.87 | - | 3.00 | - | 0.30 | 0.04 | 0.05 | 0.001 |
| 468 | 2.85 | 17.15 | - | 3.10 | 1.96 | 0.30 | 0.03 | 0.05 | 0.002 |
| 470 | 2.65 | 16.00 | - | 1.70 | 1.00 | 0.30 | 0.09 | 0.05 | 0.005 |
| 472 | 2.65 | 14.81 | - | 2.20 | 0.97 | 0.64 | 0.05 | 0.05 | 0.002 |
| 406 | 3.11 | 10.64 | 7.08 | 3.78 | 1.10 | 0.09 | 0.13 | 0.014 | 0.004 |

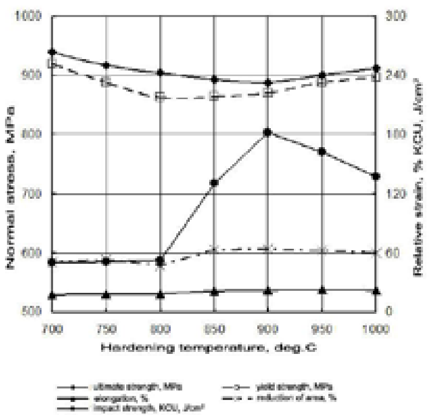



*Fig.1 Hardening temperature effect on mechanical properties of samples made of Alloy 415*

All subsequent tests were conducted on samples hardened from temperature ~850-900°C in water or in the air. In these tests the ultimate strength of the alloys was in the range of $\sigma_B$~850-950 MPa, and impact strength KCU>150J/cm²**.**

The resistance of the alloys to penetration was compared by such characteristic as an average penetration resistance (dynamic hardness – $H_D$), which was determined by relating the kinetic energy of a 45°-tip-cone-impactor to the crater volume which was calculated via the penetration depth and averaged by the results of several tests. The penetration depth was measured from the face of the sample. The tests were conducted on samples made of medium-hardness armor steel and of some titanium alloys, including the experimental alloys with β-structure.

Despite lower static hardness, dynamic hardness values of titanium alloys come very close to those of steel, and by specific dynamic hardness titanium alloys are superior to steel. The highest values of dynamic hardness and especially of specific dynamic hardness were demonstrated by experimental alloys with meta-stable β-structure S415 and S421 (Figs.2, 3). These results can imply that at normal ballistic tests the alloys with β-structure should demonstrate high resistance characteristics.

To check this assumption we conducted comparative ballistic tests of the experimental alloy with meta-stable β-structure and OT 4-1 alloy (by TT pistol, 7.62mm cartridge 57-N-134S with PST bullet) at normal impact from 5m. The test results are presented in Table 2.

Besides, we empirically selected and tested same-ballistic-resistance protective structures made of commercial alloy OT 4-1 and experimental β-alloy with high-modulus textile/polymer backing. The test results are presented in Table 3.

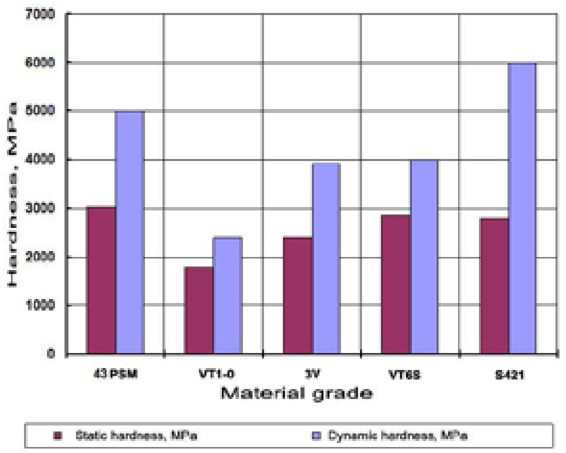



*Fig. 2 Static and dynamic hardness of titanium alloys and 4PSM steel*

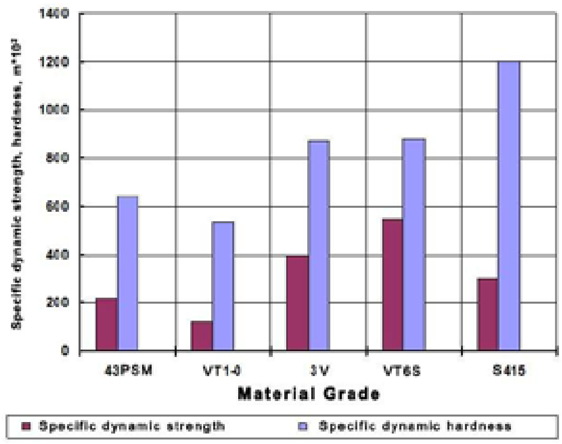



*Fig.3 Specific dynamic characteristics of titanium alloys and 43PSM steel*

*Table 2 ballistic tests of the experimental alloy with meta-stable b-structure and OT 4-1 alloy*

| Titanium alloy | Areal density of the protective structure, g/dm² | Titanium target hardness HB, kg/mm² | Remarks |
|---|---|---|---|
| OT 4-1 | 157.5 | 217 | = |
| S406 | 127 | 255 | Weight saving ~ 20% |

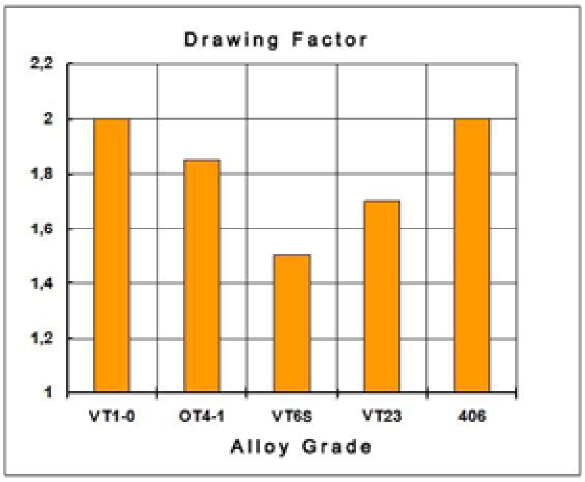
*Table 3 Commercial alloy OT 4-1 and experimental b-alloy test results*

| Titanium alloy | Backing No. | Areal density of the polymer backing, g/cm² | Remarks |
|---|---|---|---|
| OT 4-1 | 1 | 30 | |
| S406 | 1 | 20 | Saving of textile materials ~33% |
| OT 4-1 | 2 | 52 | |
| S406 | 2 | 44 | Saving of textile materials ~ 15% |

Fig.4 presents technological properties of titanium alloys with different structures at room temperature. The results of evaluation of technological characteristics of the alloys, represented in this figure, show that only the alloys with β-structure approach by their technological properties the unalloyed titanium and alloys with pseudo- α-structure OT4-1 and 3V, which can be deep-drawn in cold state.

## Conclusion

The results of our investigation point at good prospects of using titanium alloys with meta-stable β-structure for producing complex-shaped body armor components. We think it expedient to undertake a search for sparingly-alloyed β-alloys containing minimal concentrations of molybdenum, vanadium and zirconium.

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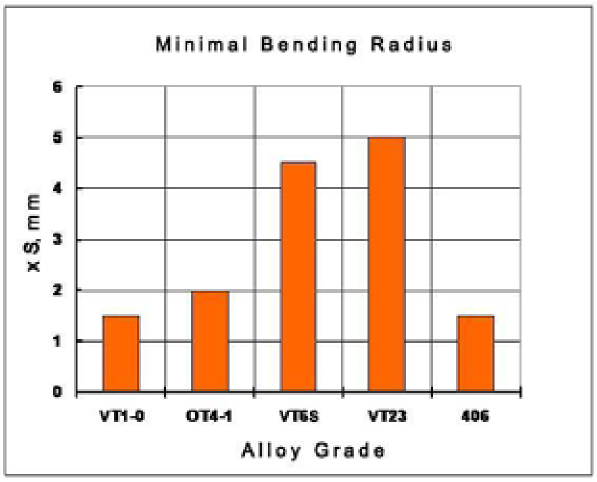


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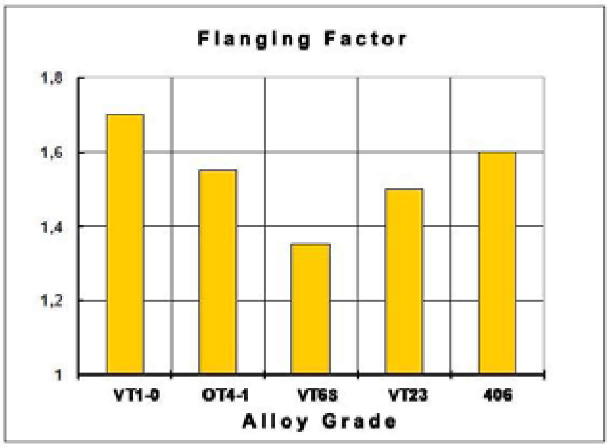


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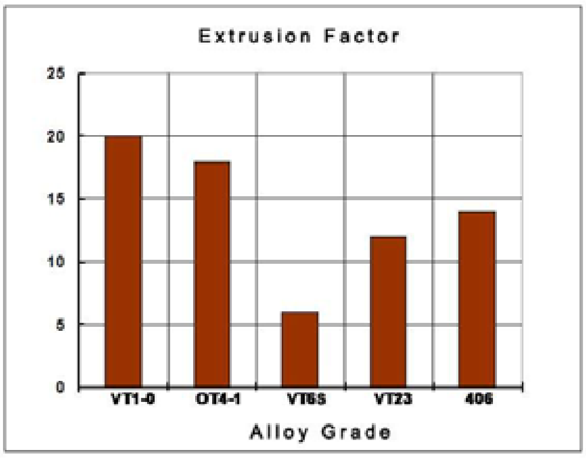


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*Fig.4 Technological properties of titanium alloys*