Study of the dynamic strength of the ultrafine-grained titanium VT 1-0

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Abstract. We report the results from the testing of the strength properties of the ultrafine-grained Ti alloy VT 1-0 under dynamic and static loading. A comparative analysis was made of the ultimate static and dynamic strength of the small-sized samples of the material subjected to severe plastic deformation. The importance of studying the dynamic strength of Ti alloys is closely related to their practical application in structures and parts operating under high dynamic loads.

1. Introduction
In the past two decades, there has been active development of ultrafine-grained (UFG) metallic materials produced by severe plastic deformation (SPD) for practical applications [1]. At present, there are many publications on the effect of the UFG structure on the mechanical and fatigue properties of Ti alloys [1-3]. However, there have been practically no studies into the dynamic strength of UFG alloys. It is known that such characteristics as the ultimate tensile strength and yield stress of ultrafine-grained alloys under dynamic loads differ significantly from the ones found during static tests. It is also known that the deformation of high-strength Ti alloys by SPD often leads to a considerable decline in their ductility. This was demonstrated through the example of the UFG titanium alloy Grade 5 (VT6 rus) and other titanium materials [3]. In its turn, the decline in the ductile characteristics of the material affects its performance properties: fatigue strength decreases, the characteristics of crack resistance and impact toughness decline, and erosion resistance also decreases [4,5]. The ductile characteristics of titanium materials normally depend a lot on the SPD processing regimes [3], which is the subject of the present study. This paper presents the data on the mechanical characteristics under dynamic and static loading of commercially pure (CP) Ti VT 1-0 processed by equal-channel angular pressing (ECAP) via different regimes, including additional thermomechanical treatment by extrusion.

2. Material and research methods
As the material for the study, we used CP Ti Grade 4 (VT 1-0 rus) in the form of hot-rolled rods with a diameter of 20 mm. To improve the internal structure, the initial rod with a diameter of 20 mm was held in a furnace at a temperature of 680 °C for 1 hour and cooled in air. As a result of this treatment, a homogeneous structure with an average grain size of 20-25 μm was formed. With a view to produce various UFG structures in the samples, we performed ECAP processing via three different regimes: 4
passes at 400 °C, 8 passes at 400 °C and 8 passes at 400 °C with subsequent extrusion at 300 °C. Recent studies [3] indicate that these ECAP regimes enable producing in Ti a UFG structure with various grain shapes and sizes. The ECAP processing was carried out via route Bc with a channels intersection angle of 120°. The structure of the produced samples was studied in a JEOL JEM-2100 transmission electron microscope.

For static and dynamic tests, we cut out small samples of reduced sizes from the rods. The gauge length of such samples was 5 mm, the width was 2 mm, and the thickness was 0.7 mm. Static tests were conducted using the method of uniaxial tension on a Shimadzu AG-50kNX universal testing machine with a rate of 10−3 s−1. Dynamic tests were conducted using an Instron CEAST 9350 drop tower impact system with an accelerator. Previously, in the paper [6], using the SPS (Sign-Perturbed Sums) method [7] the applicability of samples of such a geometry was demonstrated for the testing of materials in a wide variation range of loading parameters.

3. Results and discussion
The TEM studies of the structure after the deformation processing show that after 4 passes a UFG structure is formed with an average grain size of 450 nm. Increasing the number of passes to 8 promoted a stronger structure refinement to an average grain size of about 400 nm. The structure of the billet after ECAP processing for 8 passes and extrusion represents elongated grains with an average grain size of 300 nm.

Figure 1 shows the characteristic “stress-strain” curves for the tension of the small-sized samples in all the structural conditions. The test results indicate that the strongest condition is the UFG Ti produced by ECAP for 8 passes and extrusion. Its ultimate tensile strength (UTS) is about 920 MPa, which is much higher than the UTS after ECAP for 4 passes and 8 passes. However, its elongation to failure is lower and amounts to about 17%, whereas after ECAP the elongation to failure is over 20%. Thus, while strength grows in UFG Ti and the grain size decreases, its ductility declines, as it was observed in earlier studies [3]. The material after ECAP processing for 4 and 8 passes practically has no differences in the total strain to failure, but its static strength differs by 20%.

Therefore, it can be noted that the alloy after 8 ECAP passes has the optimum strength characteristics. When a lower strain is produced in the material, its strength declines; when a higher strain is produced in the material, its ductility declines considerably. Since the enhanced strength characteristics in the region of quasi-static loading do not guarantee good dynamic properties of the material in the region of dynamic loads, and materials from Ti alloys normally operate under dynamic loads, we continued the study of the strength characteristics.

Figure 2 presents the results of the dynamic tests of UFG Ti produced via different processing regimes. The diagram shows the experimental data and calculated curves in the framework of the structure-time approach [8,9].

\[
\frac{1}{\tau} \int_{t-\tau}^{t} \frac{\sigma(s)}{\sigma_c} ds \leq 1, \tag{1}
\]

where \(t\) is time, \(\sigma\) is the dependence of rupture stress on time, \(\sigma_c\) is the ultimate tensile strength under quasi-static loading conditions, \(\tau\) is the incubation time of fracture, which is a measure of strength in the dynamic range of the parameters of external action. As a model load, we accepted one linearly growing with time, which is closest to the experimental conditions. The parameter \(\tau\) in this set up is determined numerically by selecting the optimum correspondence of the calculated curves to the experimental curves.

The numerical values of the material’s parameters are listed in table 1. The slope of the curves in figure 2 is determined by the material’s parameter \(\tau\).
Table 1. Parameters and mechanical characteristics of the material in different structural conditions, where $\delta$ is the elongation to failure, $d_{av}$ is the average grain size.

| Condition         | $\sigma_c$, MPa | $\delta$, % | $d_{av}$, $\mu m$ | $\tau$, $\mu s$ |
|-------------------|-----------------|-------------|-------------------|-----------------|
| CG                | 495             | 30          | 25                | 39              |
| ECAP_4            | 678             | 22          | 0.45              | 31              |
| ECAP_8            | 808             | 21          | 0.4               | 25              |
| ECAP_8_Extrusion  | 917             | 17          | 0.3               | 19              |

The results of the static and dynamic tension experiments of VT 1-0 in different structural conditions show an indirect relationship between the structure and ductile characteristics, and the parameter of the material’s dynamic strength, $\tau$. Introducing into our analysis a material parameter responsible for dynamic strength has revealed the need to produce a set of strength and ductile properties in a material in order to attain high strength values under extreme loads. It has been visibly demonstrated that increasing strength in the static range of loads is not enough to achieve high deformational characteristics in the region of dynamic loads. For example, a slight decrease in the ductility parameters of the Ti alloy after additional extrusion significantly reduced the material’s dynamic strength, which is expressed in the intersection of the dynamic curves in the diagram $\sigma - \dot{\sigma}$ (figure 2). In the region of loading rates $\dot{\sigma} > 40000$ GPa/s the material after ECAP for 8 passes and extrusion has a lower strength than the alloy in the initial condition, although in the region of static loads the initial alloy’s strength is almost two times lower. The material after ECAP for 8 passes and additional extrusion is inferior already after $\dot{\sigma} > 30000$ GPa/s, which considerably reduces its application areas. The obtained results from the tension of Ti samples in the ranges of static and dynamic loads demonstrate that it is not enough to increase the material’s static strength to ensure the material’s safe operation in the region of dynamic loading. With increasing strain rate, the role of the balance of strength and ductility grows, and the high strength of the material stops being dominant in this pair.
4. Conclusions
1. Using severe plastic deformation by equal-channel angular pressing, we have produced in VT 1-0 Ti an ultrafine-grained structure with an average grain size ranging from 450 nm in the case of 4 ECAP passes to 300 nm in the case of 8 ECAP passes and additional thermomechanical treatment by extrusion.
2. The results of the mechanical tests of the small-sized samples demonstrate that the strongest condition (917 MPa) is the one after 8 ECAP passes and extrusion, but its ductility is much lower than that of the samples after 4-8 ECAP passes.
3. Using the structure-time approach, we have shown that the optimum set of strength characteristics for the use in the static and dynamic ranges of loading parameters is featured by the material after 8 ECAP passes having a combination of enhanced strength and ductility.

Acknowledgements
The authors gratefully acknowledge the financial support from Saint Petersburg State University in the framework of Call 3 project (id 26130576).

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