Investigation of strength characteristics of aluminum alloy under dynamic tension

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Abstract. The study presents the results of experimental-theoretical analysis for aluminum alloy subjected to static and dynamic tension on samples of different types. The material was tested under initial coarse-grained (CG) and in ultrafine-grained (UFG) condition. The time dependence of the tensile strength is calculated using an incubation time fracture criterion based on a set of fixed constants of the material.

1. Introduction
In the second half of the 20th century, interest in studying the behavior of solids under conditions of dynamic effects increased significantly. The area of fracture mechanics was formed. The appearance of a relatively new field of science and a large number of theoretical and experimental works did not solve all problems associated with effects of dynamic destruction, but only formed new tasks. Additional features were also revealed when new materials appeared. The main source of problems was the lack of a single fracture criterion capable of solving the problems posed in both the static and dynamic domains.

The research of behavior of materials under high rate pulse loads is of great scientific and practical interest especially considering fast development of such areas as aerospace industry and recent appearance of new materials and new methods of material treatment and processing. The identification of regularities and prediction of the behavior of materials under dynamic and static pulsed loads is the main goal of the project. Special attention in industry now paid to nanostructured materials obtained by Severe Plastic Deformation (SPD) [1], because the reliability and efficiency of modern equipment operating under conditions of high rate dynamic loads (for example, elements of gas turbine engines, parts of aircraft and spacecraft) depend on the completeness and quality of the experimental and theoretical studies carried out in the entire range of variations in the parameters of the external impact. The investigation of such materials is complicated by the specific features of small-scale samples currently obtained by SPD methods (for example, disks obtained using the method of High-Pressure Torsion (HPT) are usually up to 20 mm in diameter and up to 1–2 mm in thickness). A lot of studies of the properties of UFG materials including static strength [2, 3], fatigue [4], wear and coating adhesion [5] have been recently carried out by various research groups. Conducting experiments on high rate loading requires to develop and probe the test procedure with regard to the dimensional features of samples of nanostructured materials. To achieve the goal, a methodology was developed and experiments on dynamic tension were carried out using droptower impact systems with an accelerator.
This study presents the results of experimental-theoretical analysis of materials subjected to static and dynamic tension. The experiments were carried out on model material aluminum alloy 1230 (99.3 Al). The strength properties of these materials under high strain rates were obtained and used to analyze the tensile strengths by the incubation time fracture criterion [6, 7].

2. Materials
Experiments were carried out on model material aluminum alloy 1230 (99.3 Al). The alloy has the following composition: 99.3% of Al with additions of Fe, Si, Mn, Ti, Cu, Mg, and Zn. This material and other aluminum alloy have a wide range of practical applications in aerospace industry. The nano-materials were made by HPT processing (disks of diameter 20 mm, 6 GPa pressure, and 10 revolutions at room temperature).

The Vickers microhardness of samples was assessed for both types of the materials. The measurements were performed using Shimadzu HMV-G machine and ISO 6507-1:2005 standard. The applied load was 50 g with dwell time of 15 s. The microhardness measurements showed on average 28.6 HV for CG alloy and 53.7 HV for UFG alloy.

3. Experimental Techniques
The area of dynamic loads is of a great interest, as it is well known that the materials behavior under dynamic loading conditions significantly differs from operation under static conditions. The actual task in this area is an experimental and theoretical study of the materials properties in both the static and the dynamic regime, where the main loads are high rate pulse loads.

The earliest works in this area belong to Hopkinson [8] and Manson [9]. They used a dropping tip to produce a tension pulse. Ginns [10], using a spring mechanism to apply a dynamic load and a strain gage to measure the voltage, was one of the first who tried directly to record the dynamic stress-strain curve. Later, a lot of equipments and methods were developed.

At present, fundamental and experimental studies in the field of high-speed impulse actions are conducted at many Russian and world scientific centers. Great results have been achieved at University of Applied Sciences of Southern Switzerland, University of Texas, Stanford Research Institute, California Institute of Technology, Johns Hopkins University, and others. A lot of experience has been accumulated in experimental work. One of the main tools for implementing high-speed impulse impact is the Kolsky method using Hopkinson’s split rods [11]. There are a lot of various modifications of this method, which permits realizing compression, tension, torsion, etc. The method is based on the one-dimensional theory of propagation of elastic waves along elastic rods. According to formulas of the Kolsky method, one can determine the parametric dependence of development of stress, deformation, and strain rate in the sample during the test. However, this requires a special experimental and diagnostic knowledge, as well as significant staff experience in fixing and interpreting the received signals. These difficulties can partially be overcome using standard certified installations.

In the present study, the dynamic characteristics of the material were performed on the Instron CEAST 9350 droptower at a high strain rate. A high-energy configuration increases the velocity from 4.65–24.0 m/s. This allows one to carry out the experiment for different type of samples with automated result calculation. The samples of the first type (figure 1) were flat samples of ISO 8256 with the work part of length 10 mm and width 3 mm (Sample I). The samples of the other type (figure 2) were adapted to specific features of small-scale samples currently obtained by SPD methods. The samples has the work part of length 5 mm and width 2 mm (Sample II). The samples were cut by the electrical discharge machine ARTA 123 PRO with high precision. A special holder for small samples was also made for dynamic tension experiment.

Figure 3 shows the pulses obtained in the sensor during tensile tests under different strain rates. The signal was stable and may be used for obtaining threshold characteristic of the materials.
Figure 1. Type of samples I.

Figure 2. Type of samples II.

Figure 3. Force obtained in the machine during tensile test for different strain rates.

Experiments in static regime of deformation by tension were carried out on the Shimadzu tensile machine AG-50kNX.

4. Experimental results and theoretical investigation

In the case of slowly applied load, there occurs a destruction under the threshold value of the load amplitude. In dynamics, the strength characteristics of materials greatly differ from those obtained in the case of static loading. It can be explained by the fact that the time of loading is of the same order as the typical time of certain processes on the micro-level. This time can be described by the material constant as the incubation time parameter. For this task, for all ranges of loading an efficient criterion can be formulated in the following form [6, 7]:

$$\frac{1}{\tau} \int_{t-\tau}^{t} \sigma(s) \, ds \leq \sigma_{st},$$

(1)

where \( \tau \) is the incubation time, \( \sigma_{st} \) is the tensile strength for quasi-static loading, and \( \sigma(t) \) is the applied stress. The incubation time characterizes the material sensitivity to the rate of loading. The fracture moment \( t^* \) corresponds to the earliest realization of equality in criterion (1).
Figure 4. Tension strength versus strain rate for CG and UFG aluminum alloy for different type of samples. The theoretical line was modelled using the concept of incubation time with material parameters: for CG alloy $E = 72 \, \text{GPa}$, $\tau = 0.8 \, \mu\text{s}$, $\sigma_{st} = 80 \, \text{MPa}$; for UFG alloy $E = 72 \, \text{GPa}$, $\tau = 4.4 \, \mu\text{s}$, $\sigma_{st} = 200 \, \text{MPa}$.

The experimental results for CG aluminum alloy for Samples I and II are shown in figure 4. It shows a strain rate effect at the dynamic tensile strength. The points indicate the experimental data, whereas the curves show the theoretical line constructed by formula (1) using the material parameters $E = 72 \, \text{GPa}$, $\tau = 0.8 \, \mu\text{s}$, $\sigma_{st} = 80 \, \text{MPa}$. The obtained experimental data can serve as a basis for further studies with nano-materials because they exhibited a good compliance between the theoretical line and the experimental data for all sizes of specimens.

The experimental results for UFG materials are also shown in figure 4. The experiment was carried out with a small sample. The theoretical line is constructed by formula (1) using the material parameters $E = 72 \, \text{GPa}$, $\tau = 4.4 \, \mu\text{s}$, $\sigma_{st} = 200 \, \text{MPa}$. The obtained data showed an increase in the strength of the UFG material in the static and dynamic regimes of investigation compared with the properties of the CG material.

**Conclusion**

The test procedure for tensile testing of small samples under conditions of dynamic tension was developed using the Instron CEAST 9350 droptower. The approbation of the methodology was carried out on the model material aluminum alloy, including the comparison of the results obtained on small nontypical samples with the results obtained on standard samples. The high rate dependence of the tensile strength of samples for the model material was obtained. The experimental data after static and dynamic tension of the samples were analyzed by structural time fracture criteria. The experimental data obtained in the experiment on two types of samples agree well with the theoretical line. This allows one to carry out the further study on small-scale samples of nano-materials.

The samples were made from the aluminum alloy by the method of severe plastic deformation using high-pressure torsion procedure and then were tested like a coarse-grained analog. The UFG materials also depend on the strain rate. The severe plastic deformation significantly
changed the static and dynamic strength of the investigated material. The dynamic strength $\tau$ of UFG alloy is more than 5 times greater than the same property of CG alloy.

The experimental methods can further be used in experimental research in the field of dynamic loads. The analysis of the results can be useful in the future study of a whole range of structural materials required in the transport and aerospace industry, as well as for introducing structural temporal fracture criteria in numerical schemes.

The studies of the strain rate features using the incubation time approach provide an effective instrument for examining the fracture process that is crucial for predicting the critical parameters of external loads under various loading conditions. The theoretical analysis showed that the application of the incubation time concept allows one to determine the parameters of materials necessary to predict the strength properties under static and dynamic load conditions and permits selecting suitable materials for specific applications.

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