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Investigation of strength properties of freshwater ice

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Abstract. A study of the strength and deformation properties of freshwater ice under compression, tension and shear in a wide range of strain rates ($10^{-4} - 3 \cdot 10^{3}\,s^{-1}$) and temperatures of $-5°$ C, $-20°$ C, $-40°$ C and $-60°$ C was performed. Static stress-strain curves of ice under compression were obtained on which the identified strength properties of ice as well as compressive modulus. To determine the mechanical properties of ice at high-speed loading the Kolsky method was used with various embodiments of split Hopkinson bar. The deformation curves were obtained at various loading conditions. Thereon breaking points were defined as well as their dependence on the strain rate and temperature. Also static and dynamic strength properties of ice at splitting and circular shear were defined. Increase in the dynamic strength properties upon the static ones for all loading conditions was marked.

1. Introduction

When designing objects of aviation technology a lot of attention paid to emergency situations, accompanied by impact influence. Such situation may arise, for example, at ingress of ice pellets (hail) into the gas-turbine engine and hit the fan blade, which can lead to destruction of the turbine, the motor housing and the fuselage of the aircraft, and as a result, to casualties. For reliable strength calculation of dynamically loaded constructions aircraft engine experimental data are required on the mechanical properties (strain diagram, yield strength, tensile strength, modulus of hardening, extreme characteristics of plasticity, etc.) of metallic components of the engine as well as the mechanical properties of the ice fragments.

Mechanical properties of metallic structural elements of the engine have already been studied in detail, and to obtain the missing dynamic properties can be used known dynamic methods (the Kolsky method and split Hopkinson bar). Investigation of mechanical properties of ice is much more difficult, especially in the field of dynamic loading [1–3].

Ice is one of well-known materials, but, nevertheless, its properties are still not sufficiently studied. This is due to a large variety of structure, composition and physico-mechanical state of ice. Timing processes play significant role in the behavior of the ice [4]. Analysis of the known publications on the mechanical properties of ice indicates that there is a large variation of the strength, since on their quantitative value, beyond the main characteristics of ice (temperature, density and structure), are significantly influenced by testing procedure and dimensions of tested specimens [5].

There are two methods to determine the elastic moduli and shear: dynamic and static. The dynamic method is based on calculating of modules on the propagation velocity of the longitudinal and transverse elastic waves in the ice. The essence of the static method is to measure the magnitude of deformation of ice samples under static load.

The first experiments to determine the elastic modulus of ice under static loads were carried out at the beginning of the XIX century by Thomas Young. The obtained values of the elastic modulus of ice were varied in a very wide range – from 10^{3} to 10^{4} MPa. For many years a spread of values of the elastic modulus of ice was surprising and sometimes it was distrust to research results of different authors. More stable modulus values obtained by the dynamic test methods based on measurement of the velocity of propagation of elastic waves. The propagation velocity of sound waves in the ice is practically independent of the load and is determined only by the density of the ice, its structure, as well as by the temperature. The speed of longitudinal waves in pure ice is about 3800 m/s at a temperature of $0°$ C and rises to 4200 m/s at $-20°$ C.

The mechanical properties of the ice, i.e. ability to resist to external forces, are varying greatly depending on the temperature. The closer the temperature of the ice to melting point, the more pronounced its plastic properties and reduced strength. Lowering the temperature increases the strength of the ice [4].

In the work it was conducted a comprehensive study of the strength and deformation properties of freshwater ice in compression, tension (splitting) and circular shear in a wide range of deformation rates ($10^{-4} \div 3 \cdot 10^{3}\,s^{-1}$) and at temperatures of $-5°$ C, $-20°$ C, $-40°$ C and $-60°$ C.

2. Materials

For static and dynamic tests of ice was made four batches of ice samples of different configurations:

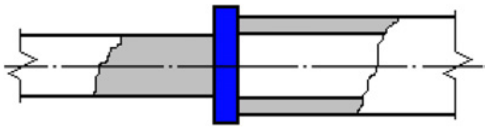

Figure 1. The test circuit for circular shear.

Type of test	Diameter, mm	Length, mm
Static compression	20	40
Dynamic compression	20	10
Static and dynamic splitting	20	20
Static and dynamic circular shear	30	10

For the manufacture of ice samples distilled water was used. Freezing water was done in a freezer at a temperature of -18° C. For each type of test the kits were made of thin-walled metal collars desired configuration. The rate of freezing of water in the collar was reduced by placing them in a heat insulating containers. In this case, the resulting ice samples have a uniform solid structure without cracks. The resulting density of the ice samples was 0.91–0.93 g/cm^3.

3. Test methods

Static properties were investigated using a universal testing machine LR5KPlus with temperature chamber. Maintaining a negative temperature in the chamber is provided by liquid nitrogen vapor.

To determine the mechanical properties of ice at high strain rates the Kolsky method was used with various realizations of the split Hopkinson bar. The tests were performed in compression by the traditional way [6], at splitting – by using Brazilian test [7]. In conventional tests at compression of cylindrical sample a compressive load is applied along the longitudinal axis of the sample. In experiments on splitting the cylindrical sample is rotated on 90° about a transverse axis, and the load applies along the diametral plane of the sample.

To determine the shear properties of ice based on a modification of the Kolsky method, wherein the supporting bar is replaced to a measuring tube (Fig. 1). The incident bar and supporting tube are working as a matrix and a punch, and in the sample thus realized circular shear (cut) by an annular surface having a diameter equal to the diameter of the bar.

Shear stress is the ratio of force $F(t)$, acting on the sample, to the square S_{sp} of circular surface corresponding to the medial surface of the sample:

$$\tau(t) = \frac{F(t)}{\pi \cdot D_{sp} \cdot L},$$

where D_{sp}– diameter of the middle surface.

The time dependence of the shear deformation is given by:

$$\gamma = \frac{U_1(t) - U_2(t)}{h},$$

here h – the height of the working part of the sample.

For comparison of diagrams obtained in this kind of tests with diagrams obtained at tension and compression, you must go to the equivalent of strain and stress through Mises criterion using the following formulas:

$$\varepsilon_{eqv} = \frac{\gamma}{\sqrt{3}}, \quad \sigma_{eqv} = \sqrt{3} \cdot \tau.$$

Sets of pressure bars for testing at compression and splitting each consist of two bars of high-strength aluminum alloy with a diameter of 20 mm and a length of 1 m. In the case of test materials in a circular shear instead supporting bar the measuring tube is used made of aluminum alloy with an inner diameter of 20.5 mm. For accurate registration of pulse passing through the ice sample and having very small amplitude (fractions of a millivolt) on a supporting bar (when tested in compression and splitting) or on the supporting tube (with shear tests) instead of foil strain gages there are glued semiconductor gages having a high gauge factor.

For the tests at low temperatures the original heat insulating chamber is used, enveloping the ends of measuring bars and the test sample placed between them. The chamber was purged with liquid nitrogen vapors for a few minutes in order to the ends of the bars before testing had a required negative temperature. The thermocouple for the sample temperature measuring was placed directly inside the chamber near the contact zone of one of the bar with the sample but without touching of the metal bar.

4. Results of investigation

After series of static tests the strength properties of ice under compression, splitting and shear were obtained. In the compressive experiments the elasticity modulus of ice was defined (by the displacement of test machine grips), which amounted to about 200 MPa at a temperature of -5°C and $\sim$310 MPa at a temperature -60°C.

Dynamic tests of ice samples were conducted at compression, tension and splitting at three values of the strain rate ($\sim 0.5 \cdot 10^3$ s^{-1}, $\sim 1 \cdot 10^3$ s^{-1} and $\sim 2 \cdot 10^3$ s^{-1} in compression) and at four negative temperatures (-5°C, -20°C, -40°C and -60°C). Required strain rates of the sample were provided by varying the impactor speed accelerated in the gas gun barrel and the required negative temperature – by controlling the rate of evaporation of liquid nitrogen.

Since during the splitting determine accurately the deformation of the sample (and, accordingly, the rate of deformation) is not possible, the stress-strain curves for this test mode were not built. Instead of the strain rate, the compression rate by the diameter was determined as the quotient of the impactor velocity (mass flow rate of end of the loading bar) to the length of the splitting plane (the diameter of the sample).

For each mode of loading (strain rate, temperature) were conducted a several (at least five) retests. Then, based on a series of curves for each mode of the test the average curve was determined with the characteristics of scatter of the experimental data (confidence intervals).

As an example in Fig. 2 the average compressive stress-strain curves at strain rate of $2 \cdot 10^3$ s^{-1} and at various test temperatures are shown. The Fig. 2a shows the time processes of stress in the sample and the strain rate (dotted

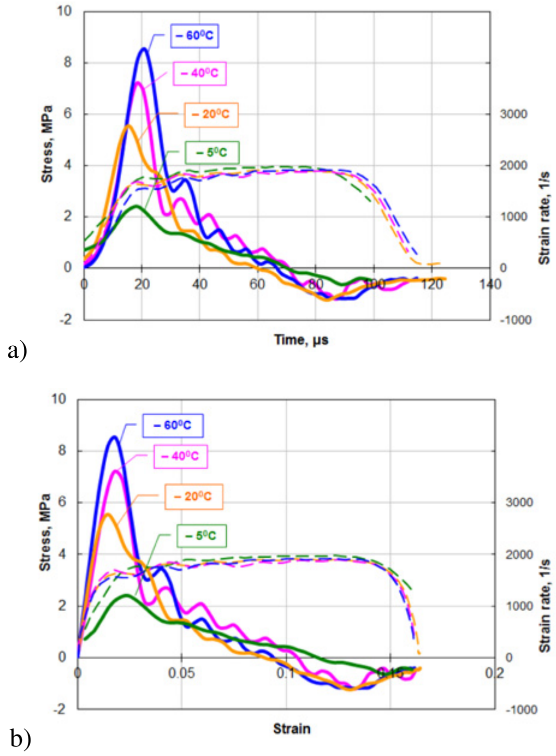

Figure 2. Effect of temperature on the dynamic stress-strain curves of ice under compression at strain rate 2000 s^{-1}.

line) as well as in the Fig. 2b – there are the same curves as a function of sample deformation.

It's clearly that temperature has small influence on the start time of destruction of the sample ($\sim$ 20 mks), whereas the strength at low temperatures increases significantly.

As a result of the cycle of the static and dynamic tests of samples of ice in different types of stress-strain state and at the four values of the negative temperature the respective stress-strain curves were obtained. According to the curve obtained for each mode of loading strength of ice was determined at compression (the maximum stress on the diagram $\sigma \sim \varepsilon$), during splitting (the maximum stress on the curve $\sigma \sim$ t) and at the annular shear (maximum stress on the curve $\tau \sim$ t).

It is interesting to compare the dynamic and static strength properties of ice. The following shows the effect of strain rate and temperature on the mechanical properties of ice under compression (Fig. 3), splitting (Fig. 4) and shear (Fig. 5).

Obtained properties of ice will be used to create a model of ice in modern computational systems for modeling situation of flying of ice fragment into a turbine of aircraft engine.

5. Summary

Mechanical properties of ice both at compression and at splitting and at shear increases with increasing of strain rate, and at lower temperatures.

Observable quite a large scatter of strength properties of ice under different loading conditions, apparently

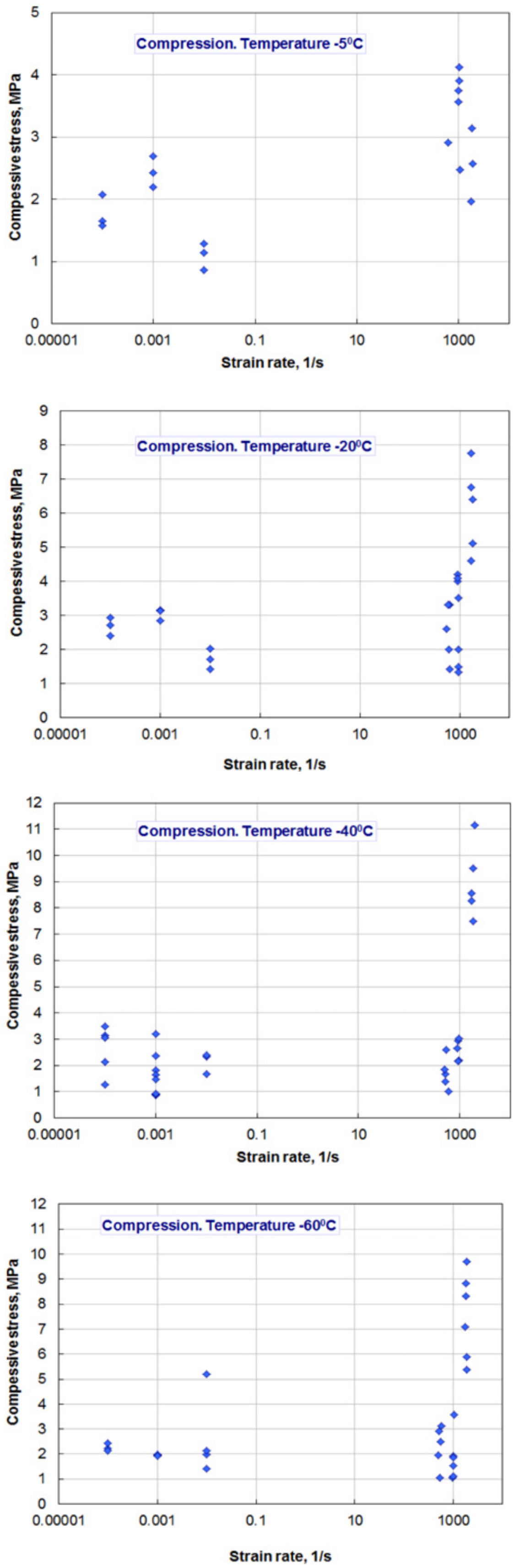

Figure 3. Effect of strain rate and temperature on strength of ice at compression.

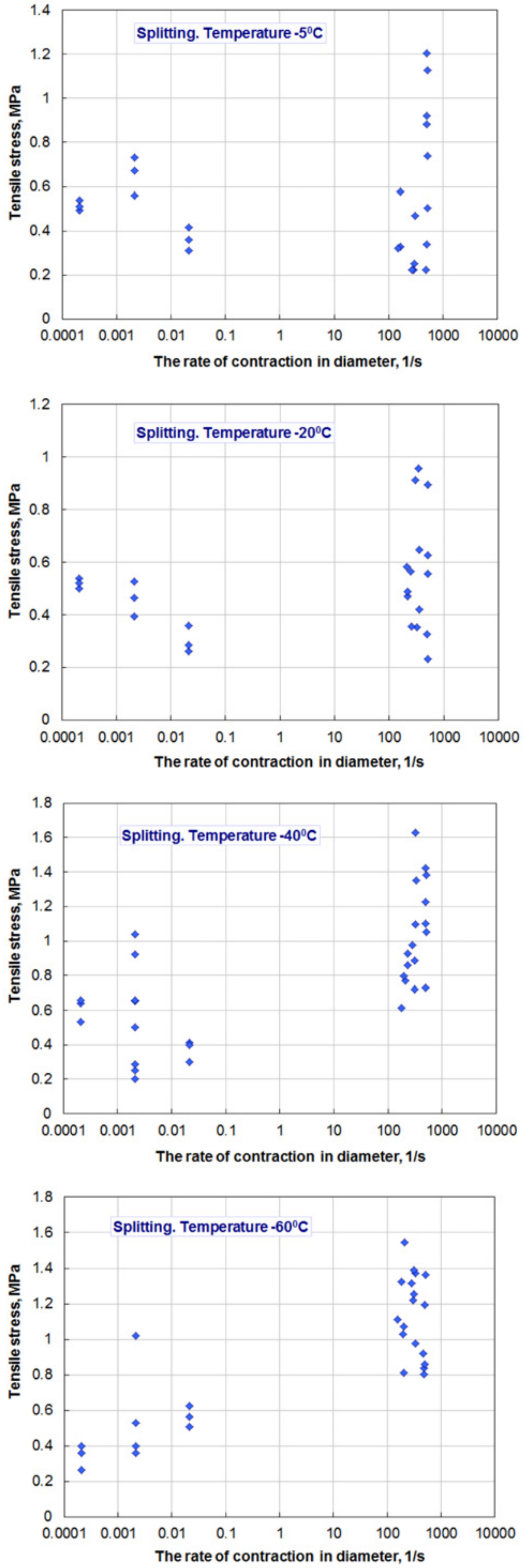

Figure 4. Effect of strain rate and temperature on strength of ice at splitting.

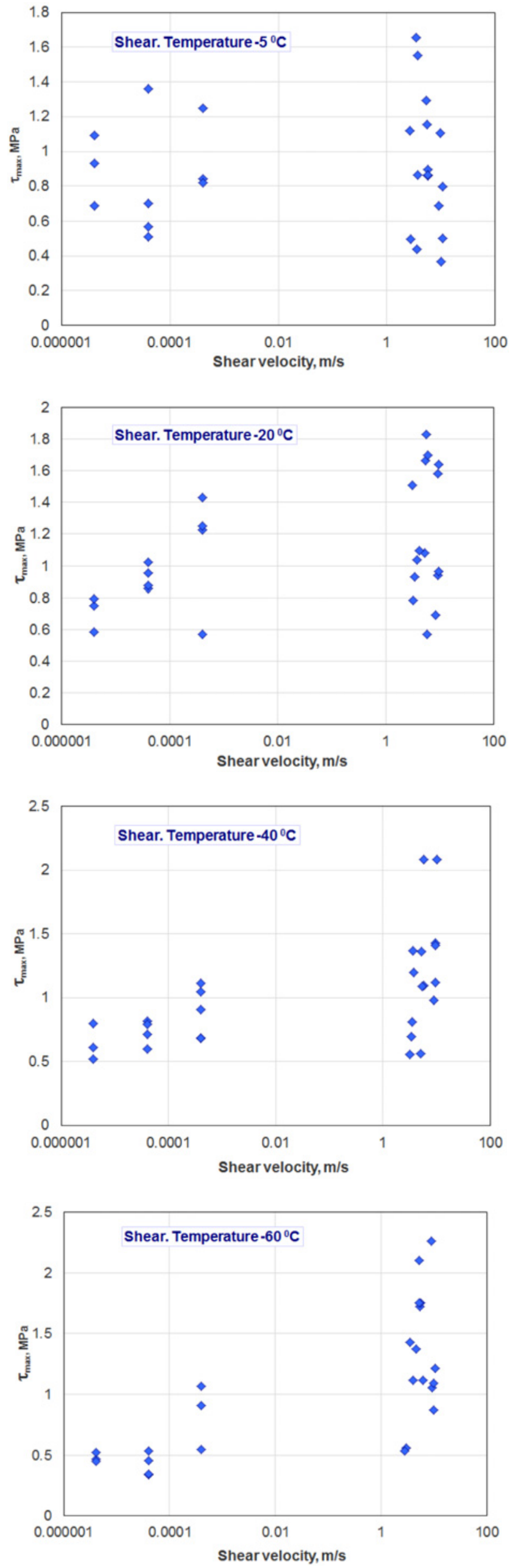

Figure 5. Effect of strain rate and temperature on strength of ice at shear.

associated with the possible heterogeneity of the structure of the frozen samples.

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