Choice of metal materials for responsible parts and vehicle
assemblies operating under the conditions of low temperatures

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Abstract. The purpose of the present study is to evaluate the cold resistance and develop an algorithm
for selecting metals that are widely used for manufacturing critical parts and components of vehicles
operating in a wide range of low temperatures.
To achieve this goal, the tests were made on impact bending of the studied metals in the temperature
range of climatic cold, followed by the study of fractures of metal samples.
The studies were carried out using methods of optical and electron microscopy and fracto-graphic
studies. During the study, data were obtained on the change in toughness, the mechanisms of metal
destruction for a wide range of low temperatures, as well as the temperature of the viscous-brittle
transition of the studied metals.
It has been found that materials with an FCC and HCP lattice exhibit greater resistance to fracture at
low temperatures. It is shown that a change in the fracture mechanism is closely related to their crystal
structure features and thermal conductivity.
As a result of the research, an algorithm for the selection of cold-resistant materials was developed,
and on its basis- a program.

Keywords: impact strength, cold resistance, thermal conductivity, crystalline structure, viscous-brittle
transition, vehicles.

Introduction
Modern vehicles operating at low temperatures have a large number of built-in diagnostic systems.
Therefore, the application of methods and means of diagnosing a vehicle makes it possible to assess the
technical condition of its main components and help its operation be more efficient and effective.
Reliability of vehicles operating in the Far North and the Arctic is achieved in another promising way, in
particular, due to the correct selection and use of cold-resistant metal materials. Among some important
properties of materials operating at low temperatures one can mention toughness and fatigue characteristics
that determine the residual life of critical components of vehicles and auxiliary equipment.
In this regard, increasing the reliability and durability of machines in the conditions of operation of the
Far North and the Arctic, makes it necessary to develop metal materials with high performance properties,
depending on their structural state with stability under both statistical and fatigue loads. Currently, a large
number of cold-resistant materials have been developed. Despite their significant diversity, only a small part
of them has got the whole range of properties necessary for reliable functioning of technical systems at low
temperatures. Depending on operating conditions, metals are subject to brittle or fatigue destruction. At low
temperatures, fracture occurs, as a rule in a brittle way. Brittle fracture is more dangerous than fatigue one.
Cold resistant materials are those that retain sufficient viscosity at low temperatures from 0 to - 269 ° C
(273 - 4 K). With decreasing temperature, this ability decreases for most metals and alloys. At critical
temperatures, shear resistance increases sharply, the metal goes into a brittle state and collapses without any
signs of plastic deformation. Resistance to such destruction is called brittle strength, and the property of
metals to break brittle with decreasing temperature is called cold brittleness. The inverse concept of cold
brittleness is cold resistance [1].
With brittle fracture at low temperatures, the crack that appears is unstable and grows spontaneously if its length (at a given stress) exceeds a certain critical value and the crack top remains sharp, comparable (along the radius at the peak) with atomic dimensions. In this case, the stresses at the edge of the cracks are sufficient to break the inter-atomic bond. The propagating crack will be bordered by a narrow zone of plastic deformation, the creation of which requires some additional energy [2]. Viscous and brittle fractures are distinguished, which differ in the size of the plastic zone at the crack top [3]. With brittle fracture, the size of the plastic zone at the mouth of the crack is small. With viscous fracture, the size of the plastic zone leading in front of the propagating crack is large, and the crack itself becomes dull at its top. Viscous failure is due to the low propagation speed of the crack. The propagation rate of a brittle crack is very high. Therefore, often brittle destruction is called "sudden", or "catastrophic" destruction. To assess the cold brittleness of steel, the fractographic control method is also used, based on measuring the fraction (in %) of the fibrous and crystalline structures of impact samples [4].

As a criterion for assessing brittleness, a percentage ratio of the areas of fibrous and crystalline fracture areas is taken. However, in practice, the temperature Tcr., at which the proportion of viscous fracture is 50%, is taken as the criterion of metal viscosity, the less Tcr., the higher the reliability of steel at low temperatures. Tcr was called - the temperature of a viscous-brittle transition. Lowering the operating temperature is accompanied by an increase in static and cyclic strength [5], with a decrease in ductility and viscosity, and therefore an increase in tendency to brittle fracture. The most important requirement determining the suitability of the material for low-temperature operation of the vehicle is the absence of cold brittleness of metallic materials. Cold brittleness is most characteristic of iron, steel, metals and alloys with FCC lattices.

During operation of the vehicle, its parts in the nodes are subjected to plastic deformation. As a result, elastic deformation energy and heat are stored in the surface layers of the parts. The energy balance during elastic-plastic deformation of the surface layers of a part in a node can be written as:

\[ \Delta E_u = \Delta E_d + \Delta E_{\text{dis}} + \Delta E_t, \]

where \( \Delta E_u \) - is the difference of mechanical energy in the node; \( \Delta E_d \) - is the elastic strain energy stored in the surface layers of the part; \( \Delta E_{\text{dis}} \) - is the dissipated energy; \( \Delta E_t \) - is the thermal energy, i.e. heat generated in the nodes from friction of parts.

The stored energy \( \Delta E_d \) is determined by the dislocation density. At low temperatures, the motion and propagation of dislocations in metals is limited due to their fixation by impurities. Therefore, the thermophysical properties of metals are of particular importance in the processes of elasto-plastic deformation of parts. In particular - thermal diffusivity and thermal conductivity. In other words, the ability of a metal to remove heat from the deformation zone at low temperatures is the determining condition for the cold resistance of metals [6]. The fact is that, as was mentioned above (Eq. 1), the energy storage of elastic deformation in the surface layers of a part at low thermal conductivity of the metal and its dissipation will be accompanied by the formation of micro-cracks. Therefore, at low values of heat capacity and thermal conductivity of metals, the occurrence of micro-cracks is the mechanism of dissipation of the stored energy of elastic deformation.

However, the heat capacity of all materials becomes extremely small at cryogenic temperatures (below 200° K), and even a small amount of heat can significantly change the body temperature. The influence of conduction electrons on the specific heat is noticeable only at temperatures close to absolute zero. The heat capacity of solids [7], which changes almost linearly at the beginning of cooling, in the cryogenic region is proportional to the third degree of absolute temperature (Debye law). In the general case, the thermal conductivity of metals depends both on the electronic structure and on the crystalline structure. Heat is dissipated both by phonons, due to vibrations of the nodes of the crystal lattice, and the motion of free electrons. The thermal conductivity of relatively pure metals depends mainly on the electronic contribution and, upon cooling, first increases, reaching a maximum, and then quickly drops to zero [7]. In metals with a BCC lattice, the electronic component of thermal conductivity is substantially determined by the presence of impurities in them and the presence of a covalent bond as a result of this, which leads to their low resistance to deformation and brittle fracture at low temperatures.

In this regard, metals with FCC and HCP lattices should exhibit high resistance to brittle fracture. Of structural steels and alloys with an FCC lattice, aluminium alloys (AMg3, AM6, D16), stainless steels, and stainless steels with titanium alloys are widely used. The indicated materials have got higher characteristics of impact strength (temperature of viscous-brittle transition) and fatigue characteristics than carbon steel with...
a bcc lattice. High characteristics of impact strength and fatigue strength of metals with FCC and HCP lattices are associated with their structure and thermo-physical properties, in particular, thermal conductivity and heat capacity [7].

When choosing a material, first of all, it is necessary to make a comprehensive review of its operating conditions and rank factors affecting the material, according to degree of their influence on the reliability of vehicles and auxiliary equipment, as well as individual units.

Among the important properties of materials operating at low temperatures one can mention their toughness and fatigue characteristics, which determine the structural stability of the material, as well as its degradation and the residual life of critical parts and assemblies.

On the whole, there is practically no data in the literature on the analysis of materials with different types of crystalline structures with an indication of the impact toughness of metals for a wide range of temperatures and the temperature of the viscous-brittle transition.

So, this work tested metals with a different type of crystal structure and revealing the temperature of a viscous-brittle transition

Materials and research methods
To conduct research and identify the features of destruction of materials used for manufacturing critical parts and components of vehicles, metals with various types of crystalline structure BCC (steel 20, steel 45, 09G2S), FCC (12X18H10T and D16) and GPU (VT8) were selected. The materials were subjected to heat treatment according to the modes indicated in Table 1. The studies were carried out on Charpy-type samples with a V-shaped concentrator (working section 8×10, manufactured in accordance with the requirements of GOST 9454–78.

Table 1 – Modes of heat treatment of the studied materials

| Material     | Type of maintenance     |
|--------------|------------------------|
| Steel 20     | Air hardening 920 °C   |
| Steel 45     | Air hardening 870 °C   |
| 09G2S        | Air hardening 930 °C   |
| 12X18H10T    | Temper 1080 °C         |
| D16          | Temper 500 °C. natural ageing |
| VT8          | Double annealing 920 °C2hr + 570 °C 1hr |

The microstructure was studied using a KYENCE-VHX 1000 optical microscope. Facto-graphic analysis was performed using a JSM-3U scanning electron microscope.

Tests for impact bending were carried out on a MK-300 pendulum copra (450 kJ potential energy supply) using the developed at NSTU n.a R.E. Alekseev device for cooling images, the principle of which is described in detail in the literature [8].

To record the temperature during samples cooling, a pt100 sensor with an operating temperature range from –196 to +100 °C (± 1 °C) was used.

The total temperature range of the tests was –80 ... + 20 ° C (temperature of climatic cold).
Preparation for testing, testing and processing of the results was carried out according to GOST 9454–78.

Experimental research. Analysis of experimental studies
At Fig. 1 see dependencies of impact strength on test temperature for the studied materials.
Fig. 1, does not show the impact strength dependence for the aluminium alloy D16, since the impact strength in the temperature range under consideration does not change and remains 20 J / cm². As was already noted, to increase the reliability of the operation of the assembly or structure, it is necessary to introduce restrictions on the material by the minimum value of impact strength, which in its turn determines the minimum operating temperature. Most often, the minimum operating temperature is determined by the temperature of the viscous-brittle transition, at which the value of impact strength is significantly reduced, and the likelihood of brittle fracture of the metal also significantly increases. To determine the temperature of the viscous-brittle transition, fracto-graphic studies of fractures of samples were carried out with the determination of the amount of fibrous (B) and brittle (X) components in the fracture. The dependence of the amount of the fibrous component in the fracture of the sample (V, %) on the test temperature for steels 20, 45, and 09Г2С is shown in Fig. 2.

An analysis of impact strength dependences (see Fig. 1) as well as the results of fracto-graphic studies of metal fractures (see Fig. 2) shows the following.
1. For metals with a BCC lattice (steel 20, steel 45 and 09Г2), a significant decrease in impact strength is observed in the temperature range under consideration (5–9 times at $t = -80^\circ C$ relative to $T = +20^\circ C$). The temperature of the viscous-brittle transition according to $T_{50}$ criterion was: for steel 09Г2S – 28$^\circ C$, steel 20 $\approx -43^\circ C$, steel 45 $\approx -43^\circ C$ (see Fig. 2).

Thus, metals with a low carbon content (steel 20 and 09Г2S) exhibit greater resistance to fracture under impact loads (have higher impact strengths) and have a lower temperature of the viscous-brittle transition. For the metals in question at room temperature, mechanisms of predominantly viscous (pitted) fracture are realized ($B = 95 ... 100\%$). With some decrease in the fracture, facets of cleavage and inter-granular fracture are found.

2. For metals with an FCC lattice (12x18N10T steel and alloy D16) a less intense drop in impact strength is observed with decreasing temperature relative to metals with a bcc lattice (see Fig. 1). For example, for aluminium alloy D16, the level of impact strength does not change with decreasing temperature, but it is at a relatively low level: 20 J/cm$^2$. Steel 12X18H10T significantly surpasses all investigated materials in terms of impact strength. When the temperature drops to temperatures of climatic cold ($t = -60^\circ C$), the level of impact strength remains at the level of 280 J/cm$^2$ C, which is explained by its high nickel content. The fracture shape of steel 12X18H10T is strongly distorted, especially at $t = +20^\circ C$, which indicates a high ductility of this material, which remains at a high level even at a temperature of $-80^\circ C$.

3. The VT8 titanium alloy (HCP lattice) is almost 2 times higher than steel 45 and alloy D16 in terms of impact strength, which, as can be seen from the dependence (see Fig. 1), changes with lower intensity. VT8 has a significant reserve of impact strength at a temperature of $t = -60^\circ C$, which remains at the level of $KCV = 40 J/cm^2$.

As shown by previous studies [9, 10], it is important, in addition to changing the toughness, to take into account the change in the fatigue characteristics of metals with decreasing temperature, which are associated with the metal crystal lattice parameter.

**Program development to select cold-resistant materials.**

To solve the question of what material to choose for manufacturing a part, assembly, or a structure it is necessary to determine a set of properties necessary for its work - mechanical, physico-chemical and, what is also important- technological.

Based on the analysis carried out in the work, we can conclude that improving the reliability of machines and structures, is mostly dependent on the right choice and use of cold-resistant materials. As was shown above, a large number of cold-resistant materials has been developed at present; each of them has its own field of rational use. Despite their great diversity, only a small part of them has the whole range of properties necessary for the normal functioning of technical systems in the Arctic.

The NSTU has developed a program that allows a comprehensive approach to select materials for vehicle assemblies and structures when working in the Arctic and the Far North. This program takes into account mechanical characteristics change within the operating temperature range, as well as the necessary technological properties of the material. The program received a certificate of registration of a computer program No. 2016811331 "Program for selection cold-resistant materials."

Thus, for the competent choice of the right material, the designer must take into account the change in mechanical characteristics at operating temperatures, know the temperature of the viscous-brittle transition, and besides take into account the impact strength index as one of the most important for choosing a material working at low temperatures.

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