Mechanical behavior investigation of constructional steels applied in amphibious all-terrain vehicle at different temperatures

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Abstract. This article presents a comparative analysis of the mechanical properties of steel 20
(ASTM 1020) and steel 09G2S (ASTM A516 Gr 70) used in the construction of amphibious
all-terrain machines developed for operation in the Arctic and Antarctic. Research included
static tensile tests, hardness measurements, fracture toughness measurements, and
fractographic studies. Experimental investigations were carried out in the temperature range
from −60°C to +50°C. As a result of the studies, the express-method for assessing the material
state according to hardness measurements is proposed.

1. Introduction
For wheeled and tracked amphibious all-terrain vehicles designed for operation in the nature
conditions of the Arctic and Antarctic, reliability of an undercarriage, a frame, and a body is
important. When analyzing metal alloys used to manufacture the undercarriage elements of such
vehicles, it should first of all pay attention to the effect of subzero temperatures on the mechanical
characteristics.

The aim of this work is to perform experimental studies of mechanical behavior of the materials
applied in the construction of wheeled and tracked amphibious all-terrain vehicles, taking into account
the temperature of operation in the Arctic and Antarctic, and to develop a simple way for assessing the material
state.

2. Materials
Constructional steels are widely used in the automotive industry for the manufacture of parts, which
should have high strength and high ductility.

Carbon steel 20 (ASTM 1020) is used in the automotive industry for the manufacture of the
undercarriage parts, the frame elements, the car body details, and others. However, in the amphibious
all-terrain vehicles designed for operation in the Arctic and Antarctic, it should be used cold-resistant
steel.
Considering the need to ensure weldability, the content of carbon and alloying elements in cold-resistant steel should be as low as possible. For the production of various parts and welded joints operating at temperatures from $-70^\circ$C to $+425^\circ$C, low-alloyed steel 09G2S (ASTM A516 Gr70) is commonly used in many industries.

In this work, a comparative analysis of the mechanical behavior of carbon steel 1020 and low-alloyed steel A516 Gr70 at different temperatures was carried out. These steels were chosen as basic materials for load-bearing elements of amphibious all-terrain vehicles, taking into account the complex of properties and price.

The actual chemical composition of the investigated steels is presented in table 1.

| Steel  | Content of alloying elements (%) |
|--------|----------------------------------|
|       | C  | Si  | Mn  | Ni  | S   | P   | Cr  | Cu  |
| 1020   | 0.20 | 0.24 | 0.37 | 0.02 | 0.01 | 0.01 | 0.04 | 0.03 |
| A516 Gr70 | 0.12 | 0.59 | 1.52 | 0.02 | 0.01 | 0.01 | 0.06 | 0.06 |

3. Experimental procedures

3.1. Static tensile tests
We subjected the sheet-type specimens to uniaxial tension with a strain rate of $10^{-3}$ s$^{-1}$ in an electromechanical testing machine Tinius Olsen H100KU. We carried out tests at temperatures of $-60^\circ$C, $+20^\circ$C, and $+50^\circ$C. During the test at $-60^\circ$C, we cooled the specimen directly in the machine jaws by dry ice. During the test at $+50^\circ$C, we heated the specimen directly in the machine jaws by a digitally controlled dryer. We monitored the temperature using a K-type thermocouple and a digital thermometer AZ8852. Also we tested the sheet-type specimens stepwise in a servohydraulic testing machine BISS Nano 25kN at temperature of $+20^\circ$C to obtain strain hardening curves.

3.2. Hardness measurements
We measured Brinell hardness by Lieb method using a combined universal NOVOTEST hardness tester. We measured the hardness on the cleaned surface, repeating the measurements several times. The inaccuracy in measuring the hardness did not exceed 120 MPa. During measurements at subzero temperatures, we cooled the specimen in the chamber by dry ice. During measurements at elevated temperatures, we heated the specimen in the chamber by a digitally controlled dryer. We monitored the temperature using a K-type thermocouple and a digital thermometer AZ8852.

3.3. Fracture toughness measurements
We made the flat rectangular specimens with a V-shaped notch and a pre-grown fatigue crack. We tested specimens on a three-point bend in a testing machine Inspect table 100 equipped with a cooling chamber at temperatures of $-60^\circ$C and $+20^\circ$C. As a quantitative characteristic of the fracture toughness, we determined the conditional critical stress intensity factor $K_C$ by the method of tangents. The relative error in measuring the conditional critical stress intensity factor $K_C$ did not exceed 10%.

3.4. Fractographic studies
In order to observe the fracture surface after specimen testing, we used scanning electron microscope TESCAN VEGA. For the best reproduction of the surface topography, we performed the fractographic studies by registering secondary electrons, which made it possible to achieve a resolution of 2 nm.
4. Results

4.1. Static strength and ductility
The main tensile properties of the investigated steels are presented in Table 2. At temperature +20°C, steel A516 Gr70 had higher yield point and tensile strength, but lower tensile elongation than steel 1020. Yield point and tensile strength of both steels decreased slightly at temperature +50°C, but increased significantly at temperature −60°C. Tensile elongation of steel 1020 increased at temperature +50°C and decreased at temperature −60°C. Tensile elongation of steel A516 Gr70 did not change.

Table 2. Tensile properties at different temperatures.

| Steel  | Temperature (°C) | Yield point (MPa) | Tensile strength (MPa) | Tensile elongation (%) |
|--------|------------------|-------------------|------------------------|------------------------|
| 1020   | +50              | 298               | 424                    | 31                     |
|        | +20              | 313               | 428                    | 28                     |
|        | −60              | 406               | 520                    | 23                     |
| A516 Gr70 | +50        | 367               | 482                    | 26                     |
|        | +20              | 382               | 500                    | 26                     |
|        | −60              | 460               | 585                    | 26                     |

Figure 1 shows how yield point and tensile strength of investigated steels depend on temperature. Figure 2 shows the strain hardening curves of investigated steels at temperature of +20°C.

The obtained strain hardening curves are well described by Ludwik equation [1]:

\[
\sigma = \sigma_0 + K \varepsilon^n
\]  

(1)

Here \( \sigma \) is applied stress, \( \sigma_0, K, \) and \( n \) are constants.
We found that $n = 0.5$ and $K = 560$ MPa. This result is consistent with the fact that the tensile test diagrams of metals and alloys after plastic deformation are described by Ludwik equation with the strain-hardening exponent $n = 0.5$ [2].

4.2. Hardness

The results of Brinell hardness measurements at different temperatures and residual plastic strains are shown in Figure 3. It’s seen that temperature and plastic deformation have a significant effect on hardness.

![Figure 3. Dependencies of hardness on temperature after different plastic strains.](image)

4.3. Fracture toughness

Table 3 presents the average values of the critical stress intensity factor of investigated steels at temperatures of $-60^\circ$C and $+20^\circ$C.

At temperature of $+20^\circ$C, fracture toughness of steel A516 Gr70 was twice as much as fracture toughness of steel 1020. At temperature of $-60^\circ$C, fracture toughness of steel A516 Gr70 decreased almost twice and fracture toughness of steel 1020 Gr70 decreased almost four times. Thus at temperature of $-60^\circ$C, fracture toughness of steel A516 Gr70 was four times more than fracture toughness of steel 1020.

The results show that steel A516 Gr70 has a better cold resistance compared to steel 1020.

| Steel ASTM | Temperature ($^\circ$C) | $K_C$ (MPa$\times$m$^{1/2}$) |
|------------|-------------------------|-----------------------------|
| 1020       | $+20$                   | 115                         |
|            | $-60$                   | 31                          |
| A516 Gr70  | $+20$                   | 243                         |
|            | $-60$                   | 129                         |

Table 3. Characteristics of fracture toughness.
4.4. Fractograms

Figure 4 and Figure 5 show fracture surfaces in the area of sustainable crack growth for steel 1020 and steel A516 Gr70 respectively. The steel specimens were destructed at temperatures of +20°C and −60°C. The photos were taken with the scanning electron microscope at ×2000 magnification.

![Figure 4](image1.png)

**Figure 4.** Fractograms for steel 1020 at temperatures of +20°C (a) and −60°C (b).

![Figure 5](image2.png)

**Figure 5.** Fractograms for steel A516 Gr70 at temperatures of +20°C (a) and −60°C (b).

Analysis of the fractograms allows drawing some conclusions about the fracture mechanisms of investigated steels. For both steels, fracture surfaces have pits at temperature of +20°C and facets of chip and intercrystalline failure at temperature of −60°C. At temperature of +20°C, the ductile fracture mechanism is realized in both steels. At temperature of −60°C, the brittle fracture mechanism is realized in steel 1020 and the mixed fracture mechanism is realized in steel A516 Gr70. This explains why with decreasing temperature fracture toughness of steel A516 Gr70 decreases less than that of steel 1020.
5. Express-method for assessing state of material
A linear regression of our experimental results gave relationship between yield strength and hardness at different temperatures shown in figure 6. It is seen that with a change in temperature from −60°C to +20°C, hardness of steel 1020 changes more than hardness of steel A516 Gr70.

![Graph showing relationship between yield strength and hardness at different temperatures]

Figure 6. Relationship between yield strength and hardness at temperatures from −60°C to +20°C.

Pavlina and Van Tyne experimentally investigated a correlation of yield strength and tensile strength with hardness for over 150 steels [3]. According to them, the yield strength of the steels exhibited a linear correlation with hardness over the entire range of strength values.

On the one hand, the yield strength strongly depends on temperature, on the other hand, on plastic strain. This means that hardness also must correlate with temperature and plastic deformation. The results obtained by us for steels 1020 and A516 Gr70 show that the correlation of hardness with temperature and plastic deformation can be described by formula:

\[ HB = HB_0 + k_T (T - T_0) + k_\varepsilon \varepsilon. \]  
(2)

Here \( HB \) is Brinell hardness at temperature \( T \) and tensile strain \( \varepsilon \), \( HB_0 \) is Brinell hardness at temperature \( T_0 \) without tensile strain, \( k_T \) and \( k_\varepsilon \) are coefficients. The correlation coefficient was more than 0.99 for both steels.

At temperature of \( T_0 = 20°C \), we found for steel 1020: \( HB_0 = 1232 \pm 18 \) MPa, \( k_T = -6.8 \pm 0.3 \), and \( k_\varepsilon = 2200 \pm 100 \), likewise for steel A516 Gr70: \( HB_0 = 1234 \pm 22 \) MPa, \( k_T = -5.2 \pm 0.4 \), and \( k_\varepsilon = 2600 \pm 100 \).

For assessing the state of the material, we propose following expression

\[ \varepsilon = \left[ \frac{HB - HB_0 - k_T (T - T_0)}{k_\varepsilon} \right] / k_\varepsilon. \]  
(3)

Thus, during the operation of an amphibious all-terrain vehicle, it is possible to carry out express-diagnostics of load-bearing elements made from investigated steels using hardness measurements.

It is clear that the dangerous level of stresses and strains in the metal will differ depending on temperature of operation. Hardness measurements allow assessing the residual plastic strain and furthermore the yield strength at any temperature of operation. This information can be used to conclude about the state of the material at that temperature.

6. Closure
The results of the investigations showed that the yield strength and tensile strength of both steels 1020 and A516 Gr70 increased significantly at temperature −60°C, but fracture toughness decreased several times. In the range from −60°C to +50°C, ductility of steel A516 Gr70 didn’t depend on temperature
unlike ductility of steel 1020, which increased at temperature +50°C and decreased at temperature –60°C.

At room temperature, the strain hardening curves of investigated steels are well described by Ludwik equation with the strain-hardening exponent \( n = 0.5 \).

The yield strength of both steels exhibited a linear correlation with the hardness in the range of temperatures from −60°C to +50°C. Temperature and plastic deformation have the significant effect on hardness. This fact allows assessing the state of the material at given temperature by hardness measuring.

At temperature of −60°C, the brittle fracture mechanism is realized in steel 1020 and the mixed fracture mechanism is realized in steel A516 Gr70.

In comparison with steel 1020, at temperature of −60°C, steel A516 Gr70 has better properties and is more preferable for the production of load-bearing elements of amphibious all-terrain vehicle designed for operation in the Arctic and Antarctic.

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**References**

[1] Ludwik P 1909 *Elements der technologischen mechanik* (Berlin: Springer)
[2] Trefilov V I et al. 1989 *Deformatsionnoe uprochnenie i razrushenie polikristallichesikh metallov* (Kiev: Naukova Dumka)
[3] Pavlina E and Van Tyne C J 2008 *J. Mater. Eng. Perform.* 17 888