The effect of low temperatures on the operability of products 20GL steel

A A Khlybov, Yu G Kabaldin, M S Anosov, D A Ryabov, V I Naumov and V I Sentyureva

Nizhny Novgorod State Technical University n.a. R.E. Alekseev, Nizhny Novgorod, Russia, email: hlybov_52@mail.ru

Abstract. The influence of low temperatures on the cold brittleness of 20GL steel is considered. Tests were carried out on the impact strength of samples of 20GL steel in the temperature range from \( t = -60 \) °C to a temperature of \( t = 20 \) °C. Fractographic studies of fractures were carried out using optical and electron microscopy. The studies were carried out after normalization, as well as after thermocyclic treatment. The research results showed that thermocyclic treatment leads to an increase in strength characteristics, grain refinement. At the same time, the temperature of the brittle-viscous transition is slightly shifted to the region of positive temperatures.

1. Introduction
The phenomenon of cold brittleness, i.e. the brittle fracture associated with the action of low temperatures on metallic materials was the first to be widely discussed in connection with the construction of the Trans-Siberian Railway at the end of the 19th century. It was noted that the rails and carts of railway cars made of cast metal suddenly collapsed when the temperature dropped below -40 °C. Even then, the problem of cold brittleness of metals, the need to study its nature and develop measures to eliminate it, were recognized as relevant. Although the problem has existed for a long time, still many aspects of the occurrence of cold brittleness remain unclear [1].

2. Materials and methods
The object of the study was 20GL steel: structural low alloy steel (according to GOST 977-88 [2]). The chemical composition of steel [3]: the base is Fe, C 0.15 - 0.25, Mg 1.2 - 1.6, Si 0.2 - 0.4, P up to 0.04

This steel is used for the manufacture of side frames for freight wagon trolleys, brake discs, gear sprockets, cast parts for pipeline fittings and automatic couplers, which are subject to the requirements for strength and toughness, operating under the action of static and dynamic loads, at temperatures up to -60 °C [4]. The mechanical properties of steel 20GL are shown in table 1.

The values of impact strength at various temperatures are shown in table 2.

Performance studies were performed on Charpy-type specimens (V-shaped incision) at different temperatures. Samples were cut from the side frame of a freight wagon trolley. The samples were heat treated in accordance with the factory technology for manufacturing the side frame. The heat treatment consisted of normalization: heating to 700 °C in 2 hours, then smooth heating to 900 °C in 1.5 hours, holding at this temperature for 4 hours and then cooling in air. This was followed by high tempering: slow heating to 670 °C for 3 hours, holding at \( T = 670 \) °C for 4 hours with further cooling in air [5, 6].

To study the microstructure of steel, the surface of the prepared samples was etched in 4% HNO₃ for 20 seconds. The microstructure was examined under a microscope KEYENCE VHX-1000.
Table 1. Mechanical properties at 20 °C, 20GL steel.

| Heat treatment                  | δ  | ψ  | KCU | σa | σ0.2 |
|--------------------------------|----|----|-----|----|------|
| Normalization 880 - 900 °C,    | 18 | 25 | 491 | 540| 275  |
| Tempering 600 - 650 °C         |    |    |     |    |      |
| Hardening 870 - 890 °C,       | 14 | 25 | 383 | 530| 334  |
| Tempering 620 - 650 °C         |    |    |     |    |      |
| Normalization                  | 20 | 35 | -   | 500| 300  |
| Hardening + Tempering          | 15 | 30 | -   | 550| 400  |

Table 2. Impact strength, kJ/m², 20GL steel.

| Assortment | Heat treatment | KCU at temperatures |
|------------|----------------|---------------------|
| Castings   | Without treatment | -60 °C | -20 °C | +20 °C |
|            |                 | 354   | 390   | 491   |

3. Analysis of results and discussion

The microstructure of steel after normalization and high tempering is shown in figure 1. From figure 1 (a), one can clearly see the ferrite-pearlite structure. With a larger increase, a small amount of nonmetallic inclusions was found (figure 1 (b)). It can be seen from figure 1 that the presented structure after normalization and high tempering is characteristic of 20GL steel.

![Figure 1](image)

Figure 1. The microstructure of the sample, 20GL steel after normalization and high tempering; a - x100; b - x500.

Impact bending tests were carried out on a MK-30A pendulum copra [7-8]. Testing of samples at low temperatures to -60 °C was carried out in a mixture of liquid nitrogen and alcohol in a cryogenic installation. At each temperature level, 5 samples were tested. According to the test results, the temperature dependence of impact strength was constructed (figure 2).

From figure 2, the temperature of the brittle-viscous transition was determined; the temperature T50, at which there is 50 % viscous and 50 % brittle components, is taken as the cold brittleness threshold [3, 5]. This approximately corresponds to half of the impact strength. The temperature Tv means that 90 % of the fiber is in the kink and the impact strength is high, and Tn corresponds to 10 % of the fiber. At -40 °C, the fiber component is significantly reduced and amounts to 10 %, the fracture becomes brittle. The ratio of 50 % fibrous + 50 % brittle components is observed at T = -20 °C, at which the transition of steel from a viscous to a brittle state occurs.
Figure 2. Determination of the brittle-viscous transition temperature of samples after normalization and high tempering.

These results are confirmed by metallographic studies of fracture of samples in the zone of crack initiation and propagation (figure 3). A similar picture is observed in the study [4].

Figure 3. Crack nucleation zone, x500:

a – fracture of the sample at T = +20 °C; b – T = 0 °C; c – T = -20 °C; d – T = -40 °C.

The data obtained show that the crack nucleation zones are similar in size to all samples, which is specified by the presence of a V-shaped concentrator. The crack propagation zone increases with decreasing temperature and at -30 °C occupies almost the entire fracture area.

Thus, starting from T = -20 °C, there is a danger of brittle fracture, this increases the likelihood of brittle fracture of the side frame of a freight wagon trolley during its operation in real conditions.

In fine-grained materials, grain boundaries not only prevent crack nucleation, but also inhibit their development, causing additional energy dissipation due to the need for reorientation of cracks at the
boundary and the generation of new microcracks in neighboring, not destroyed grains [9, 10]. In this case, microcracks are formed by the mechanism of inhibited plastic shear, in which the power of dislocation clusters is crucial, and in fine-grained grains the number of dislocation clusters is less than in coarse-grained metals [11]. Thus, in fine-grained metals or alloys with a given external stress, the initiation of microcracks is difficult, which leads to a decrease in the temperature of the brittle-viscous transition.

In [11], an equation is given that relates the transition temperature from the viscous to brittle state $T_{50}$ with a grain size $d$:

$$T_{50} = A - B \cdot \ln(d^{\frac{1}{2}}),$$

where $A$ and $B$ are constants that depend on the nature of the matrix metal and increase with increasing strength of the metal, and are little dependent on temperature [11].

Following the logic stated above, to obtain a finer-grained structure, we used the following thermocyclic processing (TCP) of the samples: heating to 920 °C, holding for 30 minutes, then transferring to another furnace with a temperature of 600 °C and holding at this temperature for 10 minutes. After that, it was again heated to 920 °C with a holding time of 30 minutes and subsequent tempering at 600 °C for 2 hours with further cooling in air [12].

Figure 4 shows the microstructure of 20GL steel after thermocyclic treatment, which became so fine-grained that a distinct structure can be seen only with an increase in x1000 (figure 4 (b)).

**Figure 4.** The microstructure of 20GL steel after TCP; a – x100, b – x1000.

On the obtained fine-grained samples after the TCP, we conducted tests to determine the impact strength at different temperatures, which are brought together and presented in figure 5.

**Figure 5.** Temperature determination brittle-viscous transition after TCP.
It follows from figure 5 that a temperature of 0 °C corresponds to 90% of the fibrous component in the fracture, as well as in the initial state. At a temperature of ~ -10.5 °C, a transition from a viscous to a brittle state is observed (50 % fibrous and 50 % brittle component in the fracture). At a temperature of -20 °C, the kink becomes 90 % brittle.

An increase in the temperature of transition to a brittle state is probably due to the fact that with a decrease in grain size, its strength increases. Grain boundaries are the main sources of vacancies in metals, and grain refinement leads to an increase in their concentration. Imperfections in the structure of grain boundaries are sources of excess energy, which causes their hardening [13]. The study of the results showed that the use of preliminary thermocyclic treatment according to the proposed modes reduces the ductility and increases the brittleness of cast 20GL steel, with a slight decrease in strength characteristics. Obviously, this may be due to some redistribution of elements (possibly phosphorus) over the network of ferrite grains. This is also confirmed by the type of kinks - kinks are roughened, especially when processing in mode 3.

The hardening associated with grain sizes is determined by the Hall-Petch formula [14]

$$\Delta\sigma_g = K_y \cdot d^{-1/2}$$  

where \(\Delta\sigma_g\) - grain boundary hardening, MPa; \(d\) - is the grain diameter, microns; \(K_y\) - coefficient determined experimentally for a given steel and alloy, MPa·m\(^{1/2}\). For ferritic-pearlitic steels, to which 20GL steel belongs (see figure 2), with high-angle grain misorientation, \(K_y\) is within 0.57 – 0.73 MPa·m\(^{1/2}\).

The fact that the strength of 20GL steel after TCP is growing is proved by measuring the Brinell microhardness before and after TTZ (table 3). From the data table 3 it follows that the hardness after TCP increases on average by 20 % [15].

| №  | Before heat treatment, HV | After heat treatment, HV |
|----|--------------------------|--------------------------|
| 1  | 1642,41                  | 1892,314                 |
| 2  | 1666,86                  | 1862,158                 |
| 3  | 1638,83                  | 2089,645                 |
| 4  | 1593,66                  | 1803,969                 |
| 5  | 1593,19                  | 1862,158                 |
| 6  | 1541,66                  | 1954,865                 |
| 7  | 1518,15                  | 1954,865                 |
| 8  | 1501,61                  | 1803,969                 |
| 9  | 1798,87                  | 2020,571                 |
| 10 | 1421,28                  | 1862,158                 |

### 4. Conclusion

Based on the conducted experimental studies, we can conclude that:

1. The performance of 20GL steel after normalization and high tempering is much higher than after a central heating station.

2. The structure after heat treatment became finer than before. The creation of such a structure implied an increase in impact strength, strength and durability. But when testing for impact strength, it was revealed that the steel after TCP passes from a viscous to a brittle state at -12.5 °C. For this reason, 20GL steel after TCP is not suitable for work at low temperatures.

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