INTRODUCTION

Refining of the characteristic elements of structure is one of the most reliable methods for raising the structural strength of steels. As a rule, attainment of the required structural strength in the overwhelming majority of steels is associated with formation of a structure of martensite. A martensitic structure includes packets, layers and laths or lamellae [1]. The contribution of different components of structure into implementation of the structural strength is not equivalent; the smaller the size of the component the higher its influence on the properties. For example, according to the data of [2], lath hardening of low-carbon packet martensite is 1 – 2 orders of magnitude higher than the hardening connected with the contribution of packet boundaries. The type of the martensite is largely determined by the composition of the steel and by the heat effect. The main [3] structural components of traditional structural steels containing 0.3 – 0.4% C after hardening are the lath and lamellar kinds of martensite. The amount of the latter depends on the content of carbon in the metal and may reach up to one fourth of the whole volume at 0.4% C. It is known that the twinned structure of lamellar martensite [4] and the formation of atmospheres of interstitial atoms [5] affect negatively the relaxation capacity of alloys and raise the susceptibility to brittle fracture as a result of limitation of the mobility of dislocations. Growth in the carbon content in austenite promotes development of bainitic transformation during cooling [6] and thus raises the critical brittle point.

Formation of block martensite [7 – 9] improves the characteristics of structural strength (primarily the crack resistance) but is fraught with considerable process difficulties (thermocycling, accelerated heating and cooling, etc.), because the duration of the austenization hold should not exceed several tens of seconds and this is possible only for articles less than 5 mm in diameter.

The properties of steels depend much on the processes that develop in the stage of austenization. In the row of strong carbide formers (niobium, titanium, vanadium) niobium hinders the growth of austenite grains the most effectively [10], while joint introduction of vanadium and niobium stimulates precipitation hardening [6].

In the end of the last century researchers developed a new class of structural steels, i.e., low-carbon martensitic steels (LCMS) [4] possessing high structural strength and unique processibility in the production of hardened parts and welded assemblies. Structural LCMS of grade 07Kh3GNM with a strength of 1000 MPa found wide use [11]. Preforms with cross section up to 150 mm from this steel can be subjected to deformation-free cooling hardening in still air right from the temperature of the deformation and can be welded in heat hardened state. The recently developed stronger LCMS of grade 12Kh2G2NMFB with elevated carbon content [12] has \( \sigma_f \geq 1200 \) MPa.

The aim of the present work consisted in studying the structure and the structural strength of heat hardened LCMS 12Kh2G2NMFB with \( \sigma_f \) of up to 1300 MPa.
METHODS OF STUDY

We studied the characteristics of mechanical properties of low-carbon martensitic steel 12Kh2G2NMFB with the following composition (in mass percent): 0.12 C, 0.31 Si, 2.11 Mn, 2.17 Cr, 1.32 Ni, 0.44 Mo, 0.15 V, 0.13 Nb, 0.011 S, 0.010 P.

The specimens for mechanical tests and structure studies were fabricated from heat treated preforms cut from the central part of bars 80 mm in diameter hardened in air from the forging temperature and of bars 125 mm in diameter hardened in air from 980°C.

The structure of the metal was studied under a NEOPHOT-32 microscope at magnifications of up to \( \times 1000 \). The fine structure was studied on foils using an EM-125 electron microscope equipped with a digital camera for displaying and storing the images.

The tests for uniaxial tension were performed in accordance with GOST 1497–84 using an INSTRON 300LX machine. The \( K_{CU} \), \( K_{CV} \), and \( K_{CT} \) impact toughness was determined in accordance with GOST 9454–78 using an IO 5003-0.3 pendulum impact machine. The specific work of failure \( A_f \), was computed as a ratio of the area under the “load – deflection” curve to the initial cross section of the specimen with a crack after bending in an INSTRON 8801 universal testing machine (the deformation rate was 0.02 mm/sec). The critical stress intensity factor \( K_c \) was determined according to GOST 25.506–85. The fracture surfaces were studied using an MBS-9 binocular microscope at magnifications of up to \( \times 30 \).

RESULTS AND DISCUSSION

The structure of steel 12Kh2G2NMFB in the initial state is represented by lath martensite (Fig. 1). The mean size of the austenite grains is \( 6 – 8 \ \mu m \), the thickness of a lath is \( 0.19 \ \mu m \). The size distribution of the structural components of the studied steel is considered in detail in [13].

After hot deformation with air cooling the structure of lath martensite provides \( \sigma_r = 1230 \ \text{MPa}, \delta = 19\%, \ KCV = 0.65 \ \text{MJ/m}^2 \) (Table 1). The impact toughness and the crack resistance grow by a factor of 1.5 – 2 after additional hardening due to refinement of the structural components of the steel in recrystallization [13].

When a specimen hardened in air from the forging temperature is loaded (curve 1 in Fig. 2), the crack grows in a step manner upon the attainment of the critical stress intensity factor. Lowering of the elastic stresses upon opening of the crack decelerates its motion until the next critical level of stress intensity is attained and the crack starts to propagate again until failure. We observed step propagation of a crack.

<table>
<thead>
<tr>
<th>Heat treatment</th>
<th>( \sigma_r, \text{MPa} )</th>
<th>( \sigma_{0.2}, \text{MPa} )</th>
<th>( \delta, % )</th>
<th>( \psi, % )</th>
<th>( KCU, \text{MJ/m}^2 )</th>
<th>( KCV, \text{MJ/m}^2 )</th>
<th>( KCT, \text{MJ/m}^2 )</th>
<th>( A_f, \text{MJ/m}^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air hardening from the temperature of hot deformation</td>
<td>1230</td>
<td>900</td>
<td>19</td>
<td>59</td>
<td>0.65</td>
<td>0.27</td>
<td>0.22</td>
<td></td>
</tr>
<tr>
<td>The same + 1-h hardening from 980°C in air</td>
<td>1300</td>
<td>1030</td>
<td>16</td>
<td>63</td>
<td>0.82</td>
<td>0.57</td>
<td>0.39</td>
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</table>

**Fig. 1.** Micro- (a) and fine (b) structures of LCMS 12Kh2G2NMFB.

**Fig. 2.** “Load (\( P \)) – deflection (\( f \))” curves obtained in static tests of specimens from steel 12Kh2G2NMFB with a crack treated in the following modes: 1) air hardening from the forging temperature; 2) rolling + 1-h hardening from 980°C in air.