This work concerns the effect of vanadium and zirconium additions to steel 36G2S on the basic mechanical properties and susceptibility to brittle fracture of medium-carbon silicon-manganese steel in order to determine the best composition for high-strength casing pipe.

The steel was melted in a 50 kg induction furnace with a basic lining. The chemical composition of the steels investigated is given in Table 1.

Ingots weighing 30 kg were forged to bars $30 \times 30$ mm in section at $1100-1150^\circ$C. The final forging temperature was $850^\circ$C. After forging, the bars were cooled in air at the rate of 50 deg/min, which is equal to the cooling rate of casing pipe with a wall thickness of 10 mm after rolling.

The strength and plastic characteristics of the experimental steels at room temperature were determined on samples $6$ mm in diameter. The ductile characteristics were determined on impact bending samples $10 \times 10 \times 55$ mm with notches of type I and type IV (GOST 9454-60).

The tendency to grain growth was determined on disks $15-20$ mm high cut from bars heated to $850-1100^\circ$C (every $50^\circ$), held 30 min, quenched in oil, tempered at $550^\circ$C for $2$ h, and cooled in air.

The microstructure was examined on the halves of the impact test samples (see Fig. 1).

The mechanical properties of all the compositions investigated satisfied the requirements of GOST 632-64 for casing pipe of strength group K (Table 2).

Fig. 1. Microstructure of steel 36G2S (a) and 34G2SF (b) in hot-rolled condition ($\times 200$).

### Table 1

<table>
<thead>
<tr>
<th>Steel</th>
<th>Composition, %</th>
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<tbody>
<tr>
<td></td>
<td>C</td>
</tr>
<tr>
<td>36G2S</td>
<td>0.38</td>
</tr>
<tr>
<td>34G2SF (0.05% V)</td>
<td>0.36</td>
</tr>
<tr>
<td>32G2SF1 (0.09% V)</td>
<td>0.33</td>
</tr>
<tr>
<td>32G2SFT2 (0.05% V, 0.075% Zr)</td>
<td>0.33</td>
</tr>
<tr>
<td>34G2STs (0.075% Zr)</td>
<td>0.37</td>
</tr>
</tbody>
</table>

Note: According to GOST specifications, the chemical composition of steel 36G2S is $0.32-0.39\%$ C, $0.4-0.7\%$ Si, $1.5-1.8\%$ Mn, $0.01\%$ S, $0.001\%$ P.
It should be noted that the compositions of some steels were at the upper limits of the nominal composition (36G2S, 34G2STs), and in these cases the strength characteristics were at the lower limit. The greatest increase in strength resulted from alloying with vanadium.

Thus, the ultimate strength of steel 32G2SF1 was ~10 kg/mm² higher, and the yield strength ~15 kg/mm² higher, than that of steel 36G2S. It should be noted that the ductile characteristics of this steel were fairly high (δ = 18%, γ = 62%). It is also characteristic that the steel with modifying additions of vanadium and zirconium (34G2SF, 32G2SF1, and 32G2SFTs) have medium carbon concentrations (in the middle of the range specified) and their mechanical properties are superior to those for strength group K casing pipe.

The addition of 0.05% vanadium to steel 36G2S increases the impact toughness to 9.7 kg·m/cm² (34G2SF), while the addition of 0.09% V (32G2SF1) increase the impact toughness to 7.3 kg·m/cm².

Thus, the tests show that steels 34G2SF, 32G2SF1, and 32G2SFTs have approximately the same strength and ductility, although steel 34G2SF contains the minimal amount of alloying elements.

The resistance of the steels to brittle fracture was determined with impact bending samples with notches of type I and type IV.

From plots of the percentage of ductile component in the fracture vs testing temperature we determined the critical temperatures of the transition to the brittle state: T₉₀ is the upper cold brittleness threshold, with 90% ductile component (D) in the fracture; T₅₀ is the middle cold brittleness threshold, with 50% D; T₄₀ is the lower cold brittleness threshold, with 10% D.

For each cold brittleness threshold we determined the corresponding value of the impact toughness (Table 3). Steel 34G2SF had the lowest cold brittleness threshold (T₉₀) with r = 1 mm; 30°C. The impact toughness was 11.0 kg·m/cm². The cold brittleness threshold of this steel was 20°C below that of steel 36G2S. The other steels investigated had a cold brittleness threshold higher than that of the original steel 36G2S. With a sharp notch (r = 0.25 mm) the order in the position of the steels in terms of their ductile characteristics was approximately the same as with a rounded notch (r = 1 mm). The cold brittleness threshold (T₉₀) was lowest for steel 34G2SF (52°C), with aₙ = 6.3 kg·m/cm². With a sharp notch, T₅₀ for steel 36G2S was 86°C, with aₙ = 6.0 kg·m/cm².

The work of crack propagation aₚ in the case of ductile fracture (90% ductile component in the fracture) was determined by the method proposed in [1] (Table 4).

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