The properties of springs depend considerably on the metallurgical quality of the steel. Melting on the base of directly reduced iron diminishes the content of admixtures in the steel. The present work concerns the mechanical properties and fracture resistance of steel 60S2G-PV melted with the use of directly reduced iron, and the operational properties of fabricated springs. It is shown that the use of steel with enhanced purity for the production of springs increases their crack resistance and static and dynamic strength.

INTRODUCTION

The strict requirements on the reliability and service life of modern cars determine the necessity for improving the quality of their parts including suspension springs that serve under high cyclic loads and are the weakest and most short-lived component of a car.

Fabrication of springs from alloy silicon steels makes it necessary to take into account the possibility of their brittle fracture, whose susceptibility depends on the content of admixtures [1 - 7].

It is known that the use of metallized raw materials for steel making raises its purity with respect to admixtures and nonmetallic inclusions and increases their hot and cold ductility and fracture resistance.

The use of steels melted on the base of a "primogenital" mixture for the production of high-strength bolts, pump and compressor pipes, railroad rails, and wheels has shown their good service properties [8 - 11].

The present paper concerns a study of the properties of silicon steels used for the production of springs. The studied steels were fabricated by the methods of direct reduction of iron and continuous casting.2

METHODS OF STUDY

Special features of the production process of steel and springs based on directly reduced iron. We chose for our study spring steel of grade 60S2G-PV produced by the Oskolskii Electrometallurgical Works (OEMK JSC). The chemical composition of the steel is presented in Table 1. OEMK JSC is the only metallurgical enterprise in Russia that produces steel from a direct reduction burden with the use of up-to-date equipment and an advanced technology. As compared with the traditional methods of melting and casting, this method provides steel of a stable composition with a diminished (by a factor of 2 - 3) content of sulfur and phosphorus, controlled content of nonferrous metals, and a high quality of the surface [4 - 6]. The steel manufactured from directly reduced charge possesses a homogeneous structure and chemical composition within one heat.

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2. The production of springs from steel 60S2G-PV was implemented with the participation of V. A. Tarasov (deceased), B. Yu. Zelichenok, T. N. Popova, and A. K. Tikhonov.

TABLE 1. Chemical Composition of Spring Steels

<table>
<thead>
<tr>
<th>Steel</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>60S2G-PV</td>
<td>0.61</td>
<td>0.72</td>
<td>1.83</td>
</tr>
<tr>
<td>60S2G (by GOST 14959 79)</td>
<td>0.55</td>
<td>0.65</td>
<td>0.70</td>
</tr>
</tbody>
</table>

Content of elements, %

<table>
<thead>
<tr>
<th>Steel</th>
<th>S</th>
<th>P</th>
<th>Cr</th>
<th>Ni</th>
<th>Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td>60S2G-PV</td>
<td>0.010</td>
<td>0.008</td>
<td>0.11</td>
<td>0.05</td>
<td>0.08</td>
</tr>
<tr>
<td>60S2G (by GOST 14959 79)</td>
<td>≤ 0.035</td>
<td>≤ 0.035</td>
<td>≤ 0.30</td>
<td>≤ 0.25</td>
<td>≤ 0.20</td>
</tr>
</tbody>
</table>
The mean content of admixtures and residual elements in the steel is 0.006% S, 0.008% P, 0.06% Ni, 0.06% Cu, < 0.010% As, 0.005% Sn, < 0.003% Pb and Sb (each), < 0.004% Zn, and < 0.001 Bi. All the grades molten by the OÉMK JSC carry a notation PV (corresponds to “direct reduction”). They meet specific specifications whose requirements exceed those envisaged by domestic and foreign standards.

The metal melted by the OÉMK JSC has the following advantages [6]:

- a high purity with respect to the content of harmful admixtures;
- an insignificant content of nonmetallic inclusions;
- a high ductility of the metal under hot and cold deformation that provides 75 – 85% camber in the hot and cold states;
- elevated mechanical properties;
- high purity of the surface of the rolled stock;
- high precision of the geometric sizes of the rolled stock.

In order to study the effect of the quality of the metal produced by the OÉMK JSC on the service characteristics of hanger springs of AvtoVAZ cars we tested a set of calibrated rolled pieces 13.6 mm in diameter from steel 60S21-PV shipped to the Orlovskii steel rolling plant. The rolled stock was used to fabricate a batch of springs for the front hanger. All the springs had been carefully controlled for correspondence to the specifications.

In accordance with the existing technology, we started by grinding the calibrated rods in a grinder, heated them to 940°C with an 11-min hold, and then coiled springs from them.

The coiled springs were heat treated as follows: quenched from 860°C in oil and tempered at 440°C. Then the springs were shot blasted for 2 – 4 min in a shot-blasting machine. The process was carefully observed. The fabricated springs were tested for static strength, elastic compliance, and endurance.

**Test methods.** The level of fracture resistance of the spring steel 60S2G-PV produced by the OÉMK JSC was compared with steel 60S2G melted by the conventional technique by testing specimens of both kinds for static and dynamic flexure. For this purpose specimens 10 × 10 × 55 mm in size with a round (r = 1 mm) and sharp (r = 0.25 mm) notch were fabricated from hot-rolled rods. The dynamic tests were performed in an impact machine and the static tests were performed in an INSTRON machine by recording the load-flexure diagram and using it to calculate the total specific work of fracture $A_{4i}$ and its components, i.e., the work of nucleation $A_{4n}$ and the work of propagation $A_{4p}$, of the crack in accordance with the method of [12].

The fracture toughness $K_{1c}$ was determined for specimens with a preliminarily deposited fatigue crack.

The service properties of the spring steel were estimated in tests of specimens with a stress concentrator under the simultaneous action of a corrosive medium, hydrogen, and mechanical stresses that simulated the actual service conditions of the springs. In accordance with this method, standard specimens $10 \times 10 \times 55$ mm in size with a sharp notch were placed in a bath with a 0.1 N solutions of sulfuric acid and an additive of a stimulator of hydrogen charging (thiourea, CH$_4$N), mounted in the INSTRON machine, and subjected to static bending within the elastic range. After this the electric voltage that provided a current density of 10 mA/cm$^2$ in the bath was switched off. Thus, the metal was charged with hydrogen and simultaneously subjected to the action of mechanical stresses. The specimen was loaded by a constant load, which corresponded to the initial coefficient of stress intensity $K_0 = 90$ MPa·m$^{1/2}$, until it fractured. The moment of the formation of a crack was detected by the change in the compliance of the loading device [13].

The results of the tests were used to determine the time before failure at the same initial coefficient of stress intensity $K_0$ and the mean speed of propagation of the crack at the given level of applied voltage.

**RESULTS AND THEIR DISCUSSION**

The values of standard mechanical properties of steel 60S2G-PV, the conventional steel 60S2G, and the requirements of the GOST 14959–79 standard are presented in Table 2. It can be seen that steel 60S2G-PV has enhanced ductility parameters at higher strength characteristics: its specific elongation is higher by 30% and the specific reduction of area is higher by 15%.

It has been established that the impact toughness of steel 60S2G-PV is higher than that of conventional steel 60S2G ($KCU = 0.275$ and 0.235 MJ/m$^2$, respectively). The tests for static flexure gave similar results (Table 3). It should be noted that steel 60S2G-PV has a higher work of crack nucleation ($A_{4n}$) and crack propagation ($A_{4p}$).

The fracture toughness of steel 60S2G-PV is 10% higher than that of steel 60S2G (Table 4). A study of the susceptibility of delayed fracture has shown that the time before failure of steel 60S2G-PV is 25% longer and the mean speed of propagation of a stable crack is 20% lower than that of steel 60S2G at the same initial coefficient of stress intensity (Table 4).

We tested the static strength of 100% springs. For 232-mm camber the springs withstand a load $P = 4400$ –

<table>
<thead>
<tr>
<th>Grade of steel</th>
<th>$\sigma_0$, MPa</th>
<th>$\sigma_{0.2}$, MPa</th>
<th>$\delta$, %</th>
<th>$\psi$, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>60S2G-PV</td>
<td>1570</td>
<td>1390</td>
<td>12</td>
<td>40</td>
</tr>
<tr>
<td>60S2G</td>
<td>1520</td>
<td>1350</td>
<td>9</td>
<td>34</td>
</tr>
<tr>
<td>60S2G (by GOST 14959–79), at least</td>
<td>1471</td>
<td>1324</td>
<td>6</td>
<td>25</td>
</tr>
</tbody>
</table>

TABLE 2. Mechanical Properties of Spring Steels