THE MECHANISM OF THE INCREASE IN FATIGUE STRENGTH DUE TO SURFACE PLASTIC DEFORMATION OF STEEL

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The substantial increase in the fatigue strength of steel due to surface plastic deformation (SPD) has been explained by the increase in the strength of the surface layer and the favorable effect of residual compressive stresses resulting from this treatment [1]. It was found in [2] that SPD is more effective with a martensitic structure than with a sorbitic structure. This conforms with the large increase in hardness and higher residual stresses as well as the lower susceptibility to damage of the surface layer in steel with a martensitic structure. However, the change in the fatigue strength after SPD cannot be explained by the improvement in the strength characteristics and residual stresses in the surface layer alone. For example, the change in the fatigue limit as a result of roller burnishing of steels 45KhNMFA and 18Kh2N4VA having a martensitic structure does not match the increase in the residual stresses and the hardness of the surface layer. The compressive stresses resulting from burnishing, the increase in hardness, and the strength of the steel in the original condition (martensitic structure) are higher for steel 45KhNMFA than for 18Kh2N4VA. However, the relative increase of the fatigue strength after roller burnishing is higher for steel 18Kh2N4VA [2]. At the same time, the use of SPD for steel with a high static strength almost completely eliminates the lag in the increase of the fatigue limit with an increase of the ultimate strength that is characteristic of high-strength materials.

There is still no explanation for the retention of the hardening effect of SPD after removal of a substantial fraction of the residual stresses by cyclic overloading.

To study other factors affecting the fatigue strength with SPD, a study was made of the amplitude-dependent internal friction (ADIF), resistance to crack development, and the fine structure. Comparative fatigue tests were also made in vacuum and in air.*

<table>
<thead>
<tr>
<th>Hardening conditions</th>
<th>Structure</th>
<th>Breaking load, kg</th>
<th>Work of fracture, kg·cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quench + temper 220º</td>
<td>Martensite</td>
<td>1197</td>
<td>25</td>
</tr>
<tr>
<td>Quench + temper 220º + roller burnish</td>
<td>1967</td>
<td>73</td>
<td></td>
</tr>
<tr>
<td>Quench + temper 220º + bulk plastic deformation</td>
<td>830</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>Quench + temper 600º</td>
<td>Sorbite</td>
<td>2450</td>
<td>424</td>
</tr>
<tr>
<td>Quench + temper + roller burnish</td>
<td>2372</td>
<td>382</td>
<td></td>
</tr>
</tbody>
</table>

The fatigue tests in vacuum (5·10⁻⁶ mm Hg) were made with symmetrical torsion of steel 45KhNMFA with a martensitic structure. Samples subjected to roller burnishing and untreated samples had the same fatigue limit [with \(\tau = 75 \text{ kg/mm}^2\) the number of cycles to failure is \((250-490)\times 10^3\)]. For samples tested in air at the same stress the fatigue limit of the burnished samples was six times that of untreated samples (387·10⁶ and 62.8·10³ cycles respectively). The same results were obtained in [3] for a titanium alloy. These data indicate that other factors in SPD, besides the original stresses and the strength characteristics of the plastically deformed surface zone, are important and, under some conditions, decisive.

A major factor in the changes resulting from SPD is the property of a very thin (so-called reduced) surface

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layer [4] which, in the process of intensive plastic deformation, takes on the properties of a hardened layer and serves as a barrier preventing movement of dislocations from the core. A high dislocation density, depending on the degree of plastic deformation, near the surface was experimentally established in [5].

The importance of the surface condition in fatigue processes* is also indicated by our data on the sharp increase of the fatigue limit of steel 45KhNMFA with a martensitic structure as the result of electropolishing (σ-1 = 88 kg/mm², as compared with 67-69 kg/mm² after mechanical finishing). After electropolishing, the hardness of the surface is more uniform (judging from microhardness measurements). The residual tensile stresses in the surface are almost unchanged as compared with the original condition (5-10 kg/mm²).

Evidently the main reason for the increase of the fatigue limit after electropolishing is the increase of the resistance to microplastic deformation of the surface layer and, as a consequence, the increase in the elastic limit of the sample.

The amplitude-dependent internal friction (ADIF) was investigated on samples of steel 40Kh1NVA with a diameter of 12 mm and gage length of 65 mm in an apparatus of the Fepple–Pertz type. Using the method of least squares, we plotted the mean logarithmic damping decrement against the mean torsional stress in the surface.

The results (Fig. 1) indicate that the damping decrement of torsional vibrations increases due to roller burnishing of steels with martensitic and sorbitic structures. This is due to the nonuniformity of the structure resulting from SPD, with a high dislocation density in the surface layer and a large gradient of macrostresses through the section.

The effect of burnishing on resistance to crack development was studied on samples of steel 45KhNMFA with a section of 10 × 8.7 mm and a notch 0.5 mm deep with a radius of 1 mm. The notch was burnished with a roller matching the radius of the notch, with a force of 2500 kg on the roller.

The depth of the crack did not exceed 0.2 mm, since the depth of strain hardening amounted to 1 mm for the martensitic steel and 0.4-0.5 mm for the sorbitic steel. Samples with a started crack were subjected to static bending tests. The maximum load and the work of fracture of samples with a started crack increases 300% due to roller burnishing of the steel with a martensitic structure (see Table 1). For the steel with a sorbitic structure no increase in the resistance to crack development due to burnishing was observed.

Electron fractographic studies revealed the difference in the mechanism of fracture for the hardened and unhardened martensitic steel (Fig. 2).

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*The effect of the roughness (surface finish grade 10-11), decarburizing, and grinding defects was excluded.