Assessment of cyclic crack resistance of surface hardened parts

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Abstract. Calculation and experimental methods for evaluating the cyclic crack resistance of materials and plain workpieces after hardening their surface layer by various technological processes are presented and argued. These methods can be used in engineering calculations to determine and designate the most effective processes for surface hardening of parts from high-strength materials and to optimize process parameters.

1. Introduction
Various technological processes of hardening their surfaces are effective means of increasing the fatigue-resistance of parts. The methods of burnishing, widely used in many areas of mechanical engineering, significantly increase not only their fatigue-resistance before crack nucleation, but also reduce the speed of their distribution evidently. Moreover, when hardening parts with a significant concentration of stresses, the process of braking of cracks can dominate the overall effect of increasing fatigue-resistance, which is expressed in a significant increase in the durability limit according to the fracture criterion.

In this regard, at the stages of designing and optimizing the technology of hardening processes, the problem of predicting not only fatigue-resistance, but also cyclic crack resistance of parts with a hardened surface layer is very urgent. Usually, methods for assessing the health of surface hardened materials and parts operating under cyclic loading are reduced to comparative fatigue tests, the purpose of which is to determine their fatigue limit taking into account variations in the methods and modes of hardening technologies or to evaluate their cyclic durability at one or several levels of stress amplitudes before fracture. Fractographic studies of fatigue fractures of specimens and parts, allowing evaluating qualitatively and quantitatively, the kinetics of the processes of nucleation and distribution of fatigue cracks should be significant addition to these studies.

2. Methodology
A feature of the fatigue fracture of parts hardened by burnishing is that the crack nucleation center can be located on the surface and at a certain depth, under the surface of the part. The location of the fatigue-resistance fracture zone is determined by the quality and stress-strain state of the surface layer of the material formed during the hardening treatment, geometry of the part in the fracture zone, level, and nature of external cyclic loads. Diagrams of fatigue fractures of samples with the possible nucleation of fatigue cracks on their surface and below the surface are shown in the figure 1.
Figure 1. Schematic views of fatigue fractures of samples: a) if there is the initiation of a crack from the surface; b) if there is subsurface nucleation.

In the figure 1 there are the following: source of fatigue crack nucleation - 1; region of stable distribution of the crack — 2 (shiny spot in the form of a part of a circle or an ellipse); region of accelerated distribution of the fatigue crack — 3 (formed immediately after the crack reaches the surface; from this moment, the crack grows rapidly, into the deep of unhardened core of the sample and in surface hardened layers final fracture of the sample, which, at stresses of the amplitude of cyclic stresses $\sigma_a$ close in magnitude to the endurance limit $\sigma_R$, exhibits a brittle fracture pattern — 4.

Samples and parts, the fatigue fracture of which begins under the hardened layer, always show greater resistance to crack distribution, and, consequently, a greater endurance limit according to the fracture criterion, in comparison with hardened samples, the fracture of which begins from the surface. This phenomenon is due to differences in the stress state at the apex of distribution of cracks during their surface and sublayer nucleation. In the case of sublayer nucleation and distribution of cracks, as a result of their minimal opening during growth, the condition of plane deformation is manifested to a greater extent than when they develop from the surface, when crack opening is more important during their distribution. The kinetics of the processes of nucleation and distribution of fatigue cracks in surface hardened samples can be revealed and the quantitative parameters determining their performance under cyclic loading can be estimated on the basis of fatigue tests with registration of the nucleation moment and kinetics of cracks, as well as on the basis of the study and analysis of fatigue fractures.

Experimental studies of cyclic crack resistance of surface hardened materials were carried out on smooth specimens of steel 30HGSN2A with a diameter in the working part of 7.5 mm, under loading by cantilevered bending. The initial surface of the samples is polished with subsequent low tempering and had a purity with the parameter $R_a=0.63 \, \mu m$. Hardening of the surface was carried out by several technological methods: bead-blasting treatment at the modes recommended in one of the works [1]; vibration hardening; diamond smoothing and rolling in a roller. One part of the samples, instead of grinding, was machined by thin turning with cutters with a negative leading edge angle, which ensured a sufficiently deep plastic deformation of the surface layer. The tests were carried out on a magnetic resonance experimental equipment with a loading frequency of 80 Hz at several voltage amplitude levels from 650 to 1200 MPa. The growth of fatigue cracks was recorded by changing the frequency of natural
vibrations of the samples (using calibration graphs), and then on their fatigue fractures by measuring the traces of cracks on a microscope [2].

Based on the analysis of the obtained experimental data, it was found that the fatigue fracture of smooth hardened samples begins below the surface only in the low-amplitude region of cyclic loading, i.e., if $\sigma_c > \sigma_a > \sigma_R$. With a decrease in the amplitude of cyclic stresses $\sigma_a$, the area of the ellipsoidal zone of stable crack distribution increases. The maximum area of this zone is observed at stress amplitudes close to the endurance limit $\sigma_R$. An increase in the stress amplitude leads to a decrease in the area of stable distribution of the crack and to a decrease in the zone of the final break. If $\sigma_c > \sigma_a$, the nucleation site of the fatigue crack is located on the surface of the sample, i.e., the mechanism of its nucleation changes. Therefore, the stress $\sigma_c$ can be some critical parameter characterizing the ability of the hardened material to resist the nucleation of a surface crack. In the figure 2 there are the experimental points and curves of the dependence of the depth of the location of the nucleation site of the fatigue crack $\delta_h$ on the amplitude of stresses for samples made of steel 30HGSN2A, where the above-mentioned regularities are clearly visible. For this steel, hardened by methods of maintaining plate pressure (MPP), the critical stress value is in the following range: $\sigma_c \approx 1100$-1300 MPa, depending on the degree and effectiveness of specific methods and modes of surface hardening.

![Figure 2. Dependence of the relative depth of the location of the fatigue fracture zone $\delta_{h}$ on the voltage amplitude $\sigma_a$ for steel 30HGSN2A: 1 – ○ diamond smoothing; 2 – Δ – rolling in a roller.](image)

It should be emphasized that the displacement of the fracture site from the depth of the hardened layer to the surface at stress amplitudes $\sigma_a > \sigma_n$ occurs in all samples, regardless of the methods and modes of hardening. The displacement of the fracture site with a change in load can be explained, firstly, by the different ratio of stress gradients from the external load and the endurance limit of the surface layer of the material at different base numbers of loading cycles, and secondly, by an increase in the relaxation of technological residual compressive stresses in deeper layers of the material with increasing external load.

There are experimental dependences of the growth of fatigue cracks obtained from fatigue tests in the figure 3. For each version of the surface hardening technology, we tested 3 samples.

It is shown on the figure, that the greatest resistance to the distribution of fatigue cracks is exhibited by samples reinforced by rolling in a roller and diamond smoothing methods, which create the largest thickness of the hardened surface layer, larger residual compressive stress, and thus provide a surface location for the fatigue fracture center.
Figure 3. Dependences of the relative length of a fatigue crack $\bar{l}$ on the number of loading cycles during the development of fatigue cracks $N_{cr}=N_{i}-N_{cr0}$ ($N_{cr0}$ is the number of loading cycles before the initiation of a fatigue crack) for samples with different surface treatment technologies: 1 – grinding; 2 – vibration hardening; 3 – fine turning with a leading edge angle $\gamma=-5^\circ$; 4 – shot peening; 5 – fine turning with $\gamma=-30^\circ$; 6 – diamond smoothing; 7 – rolling in a roller.

To describe the growth rate of fatigue cracks in the speed range $V=10^3…10^5$ mm / cycle, the Paris – Erdogan equation is widely used:

$$\frac{dl}{dN} = C (\Delta K)^n,$$

where $l$ is the crack length, $\Delta K=K_{max}-K_{min}=(1-R)K_{max}$ is the magnitude of the stress intensity factor; $R$ is the asymmetry coefficient of the stress cycle; $C$ and $n$ are material parameters.

The influence of residual stresses on the development of fatigue cracks can be taken into account by introducing a coefficient of the intensity of residual stresses $K_{res}$. The combined effect of the external cyclic load and residual stresses is taken into account on the basis of the principle of superposition, according to which the stress state near the crack when several loads acting together are determined by the stress intensity factor equal to the sum of stress intensity factors from each load separately. Moreover, it was established [3, 4] that stress redistribution caused by the appearance and distribution of cracks does not violate the superposition principle. So, the effective value of the stress intensity factor, taking into account the combined action of an external variable load and residual stresses, can be determined from the expressions:

$$\begin{align*}
\Delta K &= K_{max} - K_{res} \\
R &= \frac{K_{min} + K_{res}}{K_{max} + K_{res}} \quad \text{at} \ K_{min} + K_{res} > 0,
\end{align*}$$

$$\begin{align*}
\Delta K &= K_{max} - K_{res} \\
R &= 0 \quad \text{at} \ K_{min} + K_{res} \leq 0.
\end{align*}$$

In engineering calculations of cyclic crack resistance for cylindrical parts under bending loading and when a crack nucleates directly on the surface, taking into account the action of residual stresses, stress intensity factor at the crack front points located on the Y axis (figure 1a) can be determined by the following formulas [4, 5, 6]:

$$\begin{align*}
\Delta K &= K_{max} - K_{res} \\
R &= \frac{K_{min} + K_{res}}{K_{max} + K_{res}} \quad \text{at} \ K_{min} + K_{res} > 0,
\end{align*}$$

$$\begin{align*}
\Delta K &= K_{max} - K_{res} \\
R &= 0 \quad \text{at} \ K_{min} + K_{res} \leq 0.
• from external load according to the following formula obtained by the compliance method:

\[ K_{\text{max}} = 0.0164 \sigma_{\text{max}} d \sqrt{T}; \]  

(3)

• from residual stresses by the following formula:

\[ K_{\text{res}} = \sigma_{\text{res}} \sqrt{\frac{1.9(1.12-0.9h)}{1-d^2(1-\frac{\pi h}{a})}} \]  

(4)

During the nucleation and development of a crack under the surface, the stress intensity factor can be calculated as follows:

• from external load according to the following formula:

\[ K_{\text{max}} = \sigma_{\text{max}} \sqrt{\frac{h}{2\pi} \left( 1 - \frac{2}{3} \frac{b}{h} \cos \varphi \right)}; \]  

(5)

• from residual stresses by the following formula:

\[ K_{\text{res}} = \frac{1.41}{\pi \sqrt{4a}} \int_{F} \sigma_{\text{res}}(x,y) \times \frac{\sqrt{\left( \frac{x^2-y^2-x^2}{2 \sin \varphi - x} \right)^2 + \left( \frac{\pi \sigma_{\text{res}} - y}{2 \cos \varphi - y} \right)^2}}{F}. \]  

(6)

In the above-mentioned formulas, \( \sigma_{\text{max}} \) are the maximum stresses from the external load; \( \sigma_{\text{res}} \) are residual stresses in the surface layer; \( a, h \) are linear dimensions of the crack (figure 1); \( m=d-h; b = \frac{d}{2} - \delta_{h} \) is the distance of the center of the nucleation site under the surface crack from the neutral axis of the sample cross section; \( \varphi \) is the polar angle of the crack.

In the figure 4 there is an example comparing the experimental and calculated growth curves of fatigue cracks in unhardened and hardened samples with a plastically deformed surface layer thickness \( \delta_{pl}=0.45 \) mm, maximum value of residual compressive stresses \( \sigma_{\text{res}} \text{max}=1000 \) MPa, and stresses from an external bending moment \( \sigma_{a}=800 \) MPa (calculated curves are indicated by dashed lines). The crack area \( F \) was determined on the basis of the laws [3, 5]. Curve 3 in the zone of subsurface crack development to point A is calculated by formulas (5) and (6), and when it exits to the surface of the sample, to the right of point A, it is calculated by formulas (3) and (4). It follows from the figure that the theoretical dependences of crack growth in surface hardened samples describe well the experimental data.

**Figure 4.** Dependences of the relative area of the fatigue crack \( F=4F/\pi d^2 \) on the number of loading cycles \( N_{cr} \) for samples of steel 30HGSN2A with stress \( \sigma_{a}=800 \) MPa: 1, 2 – surface crack initiation; 3 – crack initiation under the surface; 1 – unstressed samples; 2, 3 – shot hardened samples. Point A corresponds to the crack exit to the surface (continuous lines: experiment, dashed lines: calculation).
This graph shows that the greatest resistance to the distribution of fatigue cracks have specimens reinforced with shot and, moreover, when cracks nucleate below the surface.

Based on the results of calculations using the above formulas, there are some regularities of the development of fatigue cracks in surface hardened smooth samples. When there are cracks at the same depth, in the interface between the hardened layer and the unhardened core of the material (if $\delta_h \approx \delta_{pl}$), with an increase in the value of residual compressive stresses, the number of cycles of subsurface crack development (until they reach the surface) increases (figure 5). In this case, the crack area corresponding to the moment of its emergence to the surface increases. This is due to the greater rate of crack growth from the source in the depth of the material $h_2$ than to the surface $h_1$, where the cracks develop in the zone of a large influence of technological compressive residual stresses, which cause its braking. This is visible from the crack growth curves shown in the figure 6.

![Figure 5](image1.png)

**Figure 5.** Dependence of the number of developmental cycles of a subsurface crack before it emerges on the surface on the value of residual compressive stresses.

![Figure 6](image2.png)

**Figure 6.** Dependence of the size of a subsurface crack upon its nucleation at a depth of 0.45 mm on the number of loading cycles for samples with $\sigma_{res} = -1000$ MPa.
The degree of crack braking due to the influence of residual compressive stresses is shown by the calculated curves on the graph (Figure 7). There it can be seen that if a crack nucleates in a hardened surface layer where residual compressive stresses are large enough, then its development is 25% slower than at nucleation under the same layer if the residual stresses are close to zero (for example, if there is an internal defect in the material).

![Figure 7. Dependence of subsurface crack dimensions on the number of loading cycles in the sample: 1 - unhardened ($\sigma_{\text{res}} = 0$); 2 – hardened ($\sigma_{\text{res}} = -1000$ MPa).](image)

3. Results
To assess the cyclic crack resistance of materials, taking into account the different technologies for processing their surface, the concept of cyclic fracture toughness was proposed [7, 8]. In this concept, the parameters associated with the main characteristics of cyclic strength are not associated with reaching the ultimate state at which catastrophic fracture occurs, but with reaching the conditions under which a propagating main crack occurs. In accordance with this, the crack resistance under cyclic loading is characterized by a threshold value of the stress intensity factor $K_s^1$ corresponding to straining of the main crack. The parameter $K_s^1$ is interpreted as the threshold value of $K_i$, upon reaching which a main fatigue crack is formed, which can be distributed under conditions of plane deformation. The parameter $K_s^1$ is the endurance limit of the part, determined in the dimension of the stress intensity factor, and therefore, like the endurance limit $\sigma_R$, it depends on the scale factor [9, 10]. Only in contrast to the endurance limit, which decreases with an increase in the size of a part, the value of $K_s^1$ should increase with an increase in the thickness of the part, since this increases the degree of tightness of plastic deformation at the tip of the crack when it is strained [11, 12].

For the experimental determination of the specified criterion for fracture toughness, it is necessary that the crack in the samples develop under conditions of plane deformation, which is usually achieved by increasing the cross-sectional dimensions of the sample. It was noted [13, 14] that the condition of plane deformation during crack distribution can also be ensured in small sample thicknesses, when the applied cyclic stress is close to the material endurance limit ($\sigma_{A} \approx \sigma_{R}$).

To verify the fulfillment of the conditions of plane deformation for the selected experimental samples, we use the expressions proposed in the works of Panasyuk V.V.:

$$d_{min} \geq 2.3 \frac{K^2}{\sigma_f^2}; \quad h_{min} \geq 0.48 \frac{K^2}{\sigma_f^2}$$
where $K_I$ is the stress intensity factor coefficient; $\sigma_f$ is the material flow stress coefficient; $d$ is the sample diameter; $h$ is the crack depth.

For the steel 30HGSN2A, $\sigma_f=1500$ MPa, critical value of stress intensity factor $K_{Ic}=75.8$ MPa m$^{1/2}$. For values $K_I=K_{Ic}$ we have: $d_{\text{min}}>6.4$ mm and $h_{\text{min}}>1.2$ mm. Since the samples under study have $d=7.5$ mm and, at large $K_I$ values, the real crack depth $h>2$ mm, the conditions of plane deformation at the mouth of the developing crack are satisfied.

The proposed cyclic fracture toughness can be determined by the following formula:

$$K_S^I = \sigma_R \sqrt{\pi l_S},$$

where $l_S$ is the length of a stable crack up to which the crack distributes under conditions of plane deformation.

As it was already noted during the subsurface nucleation and distribution of a fatigue crack, as a result of its minimal opening during growth, the condition of plane deformation manifests itself to a greater extent than when a crack develops from the surface.

It has been experimentally established that for surface hardened materials the parameter $K_S^I$ does not depend on the amplitude of cyclic stresses, and also that the stress amplitude $\sigma_a$ has a correlation with the depth of the location of the nucleation of the fatigue crack $\delta_h$ (figure 2).

A close correlation between $\delta_h$ and the crack length $l_S$, measured in a stable section of its development deep into the sample from the nucleation site of the fatigue crack, is shown in the graph in figure 8, where the experimentally obtained data are plotted.

![Figure 8. Experimental dependence of the size of stable crack $l_S$ on the depth of fatigue-resistance fracture zone $\delta_h$.](image)

Following the above-mentioned patterns, for a comparative assessment of the effectiveness of surface hardening methods in increasing the cyclic crack resistance of specimens and smooth parts, the equation (7) can be represented as follows:

$$K_S^I = \sigma_R \sqrt{\pi l_S}.$$  \hspace{1cm} (8)

If the stress amplitude $\sigma_a$ is close in value to the endurance limit $\sigma_R$, the crack nucleation site is usually located approximately at the hardening depth $\delta_{pl}$ (thickness of the hardened, plastically deformed surface layer) [3]:

$$K_S^I = \sigma_R \sqrt{\pi \delta_{pl}}.$$  \hspace{1cm} (9)
The fatigue limit of smooth specimens and parts hardened by surface plastic deformation during sublayer crack initiation can be estimated by the well-known expression:

\[ \sigma_R = \frac{\sigma_{RC}}{1-2\delta_{pl}}, \] (10)

where \(\sigma_{RC}\) the endurance limit of the material in the core of the part, where the weakening effect of surface defects and the positive effect of the process hardening effect are not affected; \(\delta_{pl} = \delta_{pl}/d\) is the relative thickness of the hardened surface layer of the sample or part.

From formulas (9) and (10) we obtain an expression for estimating the cyclic fracture toughness of fracture of smooth samples or parts in the following form:

\[ K_S = \frac{\sigma_{RC} \sqrt{\pi \delta_{pl} d}}{1-2\delta_{pl}} \] (11)

The results of calculations by formula (9) for several variants of surface hardening technology are given in Table 1. It also shows the experimental values of the cyclic durability of samples at the stage of distribution of a fatigue crack from its initiation to a value \(l = 0.1\) (l=0.75 mm).

**Table 1.** Calculation results for several surface hardening technology options.

| № | Surface treatment technology | Experimental endurance limit, MPa | At \(\sigma_{A}=\sigma_{R}\) \(\delta_0\), mm | \(\delta_{0.2}\), mm | \(l_a\), mm | \(\sigma_K\), MPa | \(K_S^1\), MPa m\(^{1/2}\) | \(N_{cr}\), thousand cycles |
|---|-------------------------------|----------------------------------|-------------------------------------------|-----------------|-------------|----------------|-------------------|-------------------------|
| 1 | Fine turning with \(\gamma=-30^\circ\) | 820 | 0.67 | 0.798 | 1250 | 37.6 | 27.0 |
| 2 | Fine turning with \(\gamma=-5^\circ\) | 770 | 0.33 | 0.251 | 1100 | 24.8 | 18.5 |
| 3 | Diamond smoothing | 840 | 0.70 | 0.684 | 1200 | 39.4 | 34.5 |
| 4 | Rolling in a roller | 890 | 0.85 | 0.926 | 1300 | 46.0 | 38.0 |
| 5 | Shot peening | 780 | 0.45 | 0.547 | 1100 | 29.3 | 22.0 |

Note: \(\gamma\) is an angle of the leading edge of the cutter; \(K_S^1\) is calculated value according to the formula (9); \(N_{cr}\) is the number of fatigue crack development cycles from the moment of nucleation to a size of 0.75 mm.

As can be seen from the table 1 and the data in the figure 9, the value of the cyclic fracture toughness \(K_S^1\), determined by formula (9), and the number of fracture development cycles obtained from the experiment have a satisfactory correlation.

**Figure 9.** Correspondence of the cyclic fracture toughness \(K_S^1\) and the number of crack distribution cycles from the moment of formation to a definitely specified size in surface hardened samples.
4. Conclusions
To evaluate the growth rate of fatigue cracks in surface hardened samples and smooth parts, we can use formulas (1) - (6). They make it possible to take into account the influence of technological residual stresses and the location of the center of fatigue fracture: on or under the hardened surface of a smooth part. The experimental data on the growth of fatigue cracks are well described by the proposed formulas.

The comparative assessment of the effectiveness of surface plastic deformation methods according to the criteria of cyclic crack resistance can be made on the basis of the cyclic fracture toughness index of the \( K_S^{\infty} \) material, to determine which we can use formulas (2), (3) and (5).

The proposed calculation methods for assessing the cyclic fracture toughness of a surface hardened material using the dependences obtained on the basis of fracture mechanics (development of cracks under a variable load) and using the criterion of cyclic fracture toughness with a comparative assessment of the effectiveness of the hardening methods and choosing their technological regimes give equally ranked results.

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