The strengthening technologies’ application in building steel structural elements

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Abstract. The issues of increasing the bearing capacity and fatigue resistance of structural building elements, working surfaces and edge transition sections affected by the surface plastic deformation, are considered. The regression relationships between the influencing factors’ parameters and fatigue resistance coefficients are revealed. Taking into account their relationship, the multiparametric functional relationships and systems of equations are compiled making possible to determine the optimal values of the remaining parameters in the case of the priority factor proposed parameter’s (coefficient) presence.

1. Introduction
The strengthening technologies’ application in the equipment and building constructions’ production has led to a significant increase of the structures power units responsible elements’ bearing capacity and to the widespread use of relatively cheap low-carbon structural steels, which, in the structural materials and mass production products’ constant prices rising conditions, provide the efficient production of reliable structures with a relatively low cost. In this sphere the large-scale studies [1-10] which are mainly experimental in nature and directly concern the issue of changing the metal structures’ load modes and the influence of the various factors have been conducted. The majority of these studies are targeted to solve the problems related to rising the fatigue resistance of the structural elements, and the research methodology is differentiated, in which the qualitative and quantitative assessments of particular influencing factors (load, structural, technical, operational, etc.) are considered [6-8].

The correct choice and application of strengthening technologies in structural elements, along with an increase in strength indicators, can significantly reduce the effect of some undesirable physical and mechanical phenomena (high hardness and brittleness throughout the cross section, cracking, loss of resistance to elastic deformations and vibrations, etc.). From this point of view it’s advisable to choose a method of surface plastic deformation (SPD), which allows to manage and direct the microstructure of these elements in the most frequently and significantly damaged thin surface layers ($\Delta h = 0.2...0.7\,\text{mm}$), to eliminate the surface stresses’ concentration caused by micro-roughness and to create residual compressive stresses that will relieve the external load, and to increase the wear resistance of working surfaces through these layers’ plastic deformation, at the same time maintaining the elastic properties of the middle layers in the cross section [11-15].
2. Methods

The calculations of strength and bearing capacity of structural elements use the scale coefficient $K_{ds}$, the stress concentration coefficient $K_\sigma$, the hardening coefficient $K_{\psi}$ and the total coefficient $K_{ds}=K_{/0} \times K_{\psi}$, which are the relations between the initial state and the limits of endurance of these elements for this factor, and $\bar{\sigma}_{r}$ is the limit of average (median) endurance, considering all these coefficients [7,8].

The research goal is to reveal the complex effect of the geometrical parameters’ hardening technology $(d, l)$, the stress concentration $(\bar{\sigma}_D)$, physical and mechanical properties of the surface layer $(\Delta h, H V_{\text{max}})$ of those elements and, eventually, the median endurance limit and to determine the optimal modes of hardening technology under the given values of the coefficients $K_{ds}, K_{\sigma}, K_{\psi}, K_{dd}$. The results of the earlier obtained fatigue tests (665 series) were classified as initial data [1-8]. The most common form of SPD – the working surfaces’ plastic deformation of the structural elements with a ball or roller strengthening tool [4] was chosen.

The priority factors influencing the problem under study are the values of the geometric parameters of elements and nodes $(d, l)$, $(\Delta h, H V_{\text{max}})$ and $(\bar{\sigma}_D)$, which form the composition of the main subgroup of these values. The related coefficients’ values $K_{ds}, K_{\sigma}, K_{\psi}, K_{dd}$ and $\bar{\sigma}_{r}$ are included in the second subgroup, and all the subgroups are included in one common multiparametric function, which is the aggregate mathematical model of the problem under study:

$$F[(\Delta h, d, \bar{\sigma}_{r}), (K_{ds}, K_{\sigma}, K_{\psi}, K_{dd}, \bar{\sigma}_{r})] = 0. \quad (1)$$

which in practical calculations is used in the form of the regression parametric equations system [16,17,18].

The mathematical model (1) can be represented as a separate system composed of two groups of parametric functions that are formed in accordance with the design requirements of the structure:

1) the separate connections $K_{ds}K_{\sigma}K_{\psi}K_{dd}$ and $\bar{\sigma}_{r}$ from $\Delta h, d, \bar{\sigma}_{r}$ by the priority influencing factor,
2) the interdependent relationships of the same coefficients from $\Delta h, d, \bar{\sigma}_{r}$.

The choice of the equations system type is based on the functional relationships reliability degree included in this system of indexes that allows to choose the option that most effective reflects the studied factors changes’ characteristics in the design, engineering and operational processes from the equations’ systems and to determine the optimal values of their parameters. Forming the model indicators’ subgroups for:

1) the influencing factor priority case gives the following possible options: 1, 3, 5,
2) $(\Delta h, d, \bar{\sigma}_{r})$, 3. $(d, \Delta h, \bar{\sigma}_{r})$, 5. $(\bar{\sigma}_{r}, \Delta h, d)$,
3) $(\Delta h, \bar{\sigma}_{r}, d)$, 4. $(d, \bar{\sigma}_{r}, \Delta h)$, 6. $(\bar{\sigma}_{r}, d, \Delta h)$. \quad (2)

In (2) of the values combinations $\Delta h, d, \bar{\sigma}_{r}$ the options 1, 3 and 5 are of practical significance, which have a significant impact on fatigue phenomena in structures. Considering this, the following systems of parametric equations have been compiled for these three options in the combinations 1, 3 and 5 [13,19,20]:

| I | II | III |
|---|---|---|
| $K_{ds} = f_1(\Delta h, d, \bar{\sigma}_{r})$, | $K_{ds} = \psi_1(\Delta h, \bar{\sigma}_{r}, d)$, | $K_{ds} = \psi_1(\Delta h, \bar{\sigma}_{r}, d)$, |
| $K_{\sigma} = f_2(\Delta h, d, \bar{\sigma}_{r})$, | $K_{\sigma} = \psi_2(\Delta h, \bar{\sigma}_{r}, d)$, | $K_{\sigma} = \psi_2(\Delta h, \bar{\sigma}_{r}, d)$, |
| $K_{\psi} = f_3(\Delta h, d, \bar{\sigma}_{r})$, | $K_{\psi} = \psi_3(\Delta h, \bar{\sigma}_{r}, d)$, | $K_{\psi} = \psi_3(\Delta h, \bar{\sigma}_{r}, d)$, |
| $K_{dd} = f_4(\Delta h, d, \bar{\sigma}_{r})$, | $K_{dd} = \psi_4(\Delta h, \bar{\sigma}_{r}, d)$, | $K_{dd} = \psi_4(\Delta h, \bar{\sigma}_{r}, d)$, |
| $\bar{\sigma}_{R_{(v)}} = f_5(\Delta h, d, \bar{\sigma}_{r})$, $\bar{\sigma}_{R_{(v)}} = \psi_5(\Delta h, \bar{\sigma}_{r}, d)$, $\bar{\sigma}_{R_{(v)}} = \psi_5(\Delta h, \bar{\sigma}_{r}, d)$, |
| $n(x = \Delta h)$, | $(x = d)$, | $(x = d)$, |

This movement of the arguments $x = \Delta h, d$ and $\bar{\sigma}_{r}$ with the constant values of $K_{ds}$, $K_{\sigma}$, $K_{\psi}$, $K_{dd}$, $\bar{\sigma}_{R_{(v)}}$ allows to obtain orthogonally located functions’ classes in the coordinate system $(x, y)$, and
in the three-dimensional coordinate system \((K, x, y)\) - the surfaces formed by the 3D principle (Figure 1).

\[ \Delta h_{mm} \quad d_{mm} \quad \bar{\sigma}_{\eta} \]

(a) \hspace{1cm} (b)

**Figure 1.** The surfaces of function \(K_{\nu\sigma} = \varphi_3 (d, \Delta h, \bar{\sigma}_{\eta})\) for \(\bar{\sigma}_{\eta 1} = 1.0\) (a) and \(\bar{\sigma}_{\eta 4} = 2.75\) (b).

### 3. Results

In this paper, the priority factor is considered to be the SPD method, and for the quantitative assessments’ purpose, the parameters combination 1 from (2) and a system of functions I from (3) are taken. The values of \(\bar{\sigma}_{R(\nu)}\) are calculated on the fatigue tests’ results of 10...1 of the samples series (in each series - 12 ... 15 samples) and the coefficients \(K_{d\sigma}, K_{\sigma}, K_{\nu\sigma}, K_{\sigma D}\) based on them, were determined and grouped by the parameters \(\Delta h, d, \bar{\sigma}_{\eta}\):

\[
\begin{align*}
\Delta h_{mm} & \quad 0.00 \quad 0.05 \quad 0.10 \quad 0.15, \\
 d_{mm} & \quad 7.5 \quad 10.0 \quad 15.0 \quad 20.0, \\
 \bar{\sigma}_{\eta} & \quad 1.00 \quad 1.25 \quad 1.75 \quad 2.75.
\end{align*}
\]

The received 4 x 4 x 4 = 64 calculated points in the coordinate system \((x, y)\) are grouped by 4 - in accordance with the above-mentioned scheme \(\Delta h, d, \bar{\sigma}_{\eta}\) and for each of \(K_{d\sigma}, K_{\sigma}, K_{\nu\sigma}, K_{\sigma D}\), are compiled with 16 parametric equations (a total of 80 equations). Using the modern technical computing system (Wolfram Mathematica and others), the regression equations of 1-3 degrees were obtained for the functions (3) and the options providing the value of the determination coefficient \(R^2>0.9\) were chosen. As an example, the equations of the function \(K_{\nu\sigma} = f_3(\Delta h, d, \bar{\sigma}_{\eta})\) are given (Table), and the similar power equations are also obtained for the other coefficients and \(\bar{\sigma}_{R}\) [16,17,18].

In accordance with the obtained regression equations, the functions’ graphs of the system I \((\Delta = \Delta h, \text{Figure 2})\) are made, and the nature of changes in these coefficients and \(\bar{\sigma}_{R}\) - depending on the surface hardening degree is considered.

#### 3.1. The SPD influence on geometric parameters

\(\Delta h, d, \bar{\sigma}_{\eta}\) have the opposite effect on the fatigue resistance index \(K_{d\sigma}\). If the probability of microstructural irregularities and defects increases with increasing the size and loading by the cyclic bending or torsion, the surface layers’ stress increases in the areas where fatigue damages are formed and developed, then when using SPD, the strength of these layers increases and micro geometry gets improved - there are residual compression stresses that relieve the working stress, and as a result, the wear resistance and fatigue resistance of the structural elements increases [19].

For the initial tests \((\bar{\sigma}_{\eta} = 1.00, \Delta h = 0)\), when \(d = 7.5 \ldots 20.0 \text{ mm}\), the values of \(K_{d\sigma}\) are changed in the range \(K_{d\sigma} = 1.00 \ldots 0.81\), and with the surface-hardened layer rising \((\Delta h = 0.15 \text{ m})\) \(K_{d\sigma} = 1.00 \ldots 0.9\) (Figure 2a): for a diameter \(d = 20 \text{ mm}\), the function gradient \(K_{d\sigma} = f_3(\Delta h, d, \bar{\sigma}_{\eta})\) is also increased. When the stresses are revised and taken into account together, the hardening effect increases, and the specified functions move to the zone of values \(K_{d\sigma} = 0.94 \ldots 1.00\) (Figure 2a).

**Table 1.** The function \(K_{\nu\sigma} = f_3(\Delta h, d, \bar{\sigma}_{\eta})\) equation
3.2. The SPD influence on the stress concentration coefficient

In this case, the surface hardening efficiency is as high as the stress concentration is marked significantly. In this section, the SPD creates the enabling conditions for reducing the stress concentration due to residual compressive stresses that have occurred due to the concentrator edge contour’s plastic deformation. But this process is fading and after a certain value, further \( \Delta h \) rising does not lead to a significant decrease in the value of \( K_\sigma \) (Figure 2 b). The SPD application in the intervals \( \bar{\alpha}_{\sigma_2}, \bar{\alpha}_{\sigma_3}, \bar{\alpha}_{\sigma_4} \) reduces the value of \( K_\sigma \) by 16\%…17\%, 20\%…25\%, 28\%…30\%, accordingly. At the same time, the structural elements dimensions influence at high stress concentrations (\( \bar{\alpha}_{\sigma_3} \)) is insignificant (Figure 2 b).

![Graph](image-url)
3.3. The SPD influence on the hardening coefficient function

$K_{\sigma\sigma}$ is a monotonically growing function in the range $\Delta h = 0 \cdots 0.15 \text{ mm}$, and the hardening efficiency is maximal at a significantly stress concentration (Figure 2c). In the range $\Delta h = 0 \cdots 0.15 \text{ mm}$, for the flat elements and the elements with stress concentrators, the values of $K_{\sigma\sigma}$ reach $K_{\sigma\sigma} = 1.14 \cdots 1.26$ and $1.25 \cdots 1.37$, $1.42 \cdots 1.59$, $1.61 \cdots 1.74$ - accordingly, the extreme right values of the $K_{\sigma\sigma}$ intervals coincide to the size $d = 20 \text{ mm}$.

The change nature in the $K_{\sigma\sigma}$ function and its interval values confirm the point of view of the hardening efficiency increasing at the substantial stress concentration. This allows us to solve one important practical problem: for an element with a certain value $K_{\sigma}$, it is possible to choose the optimal hardening mode, which completely compensates for the stress concentration.

3.4. The SPD impact on the total coefficient function

Considering the structure of $K_{\sigma\sigma\sigma\sigma}$ and the coefficient functions’ gradients (Figure 2a, b, c), $K_{\sigma\sigma\sigma\sigma}$ in integral form generalizes their functional features and basically repeats the form of the function $K_{\sigma}$ as the most significant coefficient in terms of $K_{\sigma}$ as well as the function gradient, with which it is directly proportional.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{Function of the system I: (a) $K_{\sigma\sigma} = f_1(\Delta h, d, \bar{\sigma}_\sigma)$, (b) $K_{\sigma\sigma} = f_2(\Delta h, d, \bar{\sigma}_\sigma)$, (c) $K_{\sigma\sigma\sigma\sigma} = f_3(\Delta h, d, \bar{\sigma}_\sigma)$, (d) $K_{\sigma\sigma\sigma\sigma} = f_4(\Delta h, d, \bar{\sigma}_\sigma)$, (e) $K_{\sigma\sigma\sigma\sigma} = f_5(\Delta h, d, \bar{\sigma}_\sigma)$. Extreme notation: (1,1,⋯,1) – flat elements, (2,1,⋯,2,4), (3,1,⋯,3,4), (4,1,⋯,4,4) – elements with $\bar{\sigma}_\sigma$ values. Indexes 1,⋯,4 meet the values $d = 7.5$, 10.0, 15.0 and 20.0 mm.}
\end{figure}
interrelated (Figure 2d). But in contrast to \( K_{\sigma} \), the gradient of the \( K_{\sigma D} \) function in the range \( \Delta h = 0 \cdots 0.15 \text{mm} \) is significant, that is why there is a monotonous and substantial decrease in \( K_{\sigma D} \) at the high stress concentrations and \( \Delta h = 0.15 \text{mm} \).

For the flat elements, the change in the function \( K_{\sigma D} \) is almost rectilinear, and with increasing the stress concentration it becomes curved. The influence of the element size on \( K_{\sigma D} \) is significant when it is not hardened (Figure 2d) and there is a large stress concentration, but concurrently with the increase in the hardening degree, \( K_{\sigma D} \) decreases significantly (Figure 2d, \( \Delta h = 0.15 \text{ mm} \)). The coefficient function \( K_{\sigma D} \) qualitatively and quantitatively reveals the common trend and the value of the hardening process impact on the fatigue resistance indicators, which is ultimately expressed in a change in the limit value of the main one - the long-term endurance \( \tilde{\sigma}_R \), which is widely used in design and verification calculations of the structural elements’ strength.

3.5. The SPD influence on the endurance \( \tilde{\sigma}_R \) limit

The values of \( \tilde{\sigma}_R \) are the considered final, they are formed as a result of the all the factors’ influence on the elements’ fatigue and, first of all, the stress concentration. Since the interaction of the values \( \tilde{\sigma}_R \) and \( K_{\sigma D} \) is reversed in these calculations, their absolute values have the opposite direction under the influence of the observed factors with approximately the same functions gradient (Figure 2d).

With the hardening level increasing (up to \( \tilde{\sigma}_R = K_{\sigma D} \text{ mm} \)), which is technologically possible, the level of increase in the limits of endurance will be more significant, which is the main advantage of the SPD efficiency, which softens the stress concentration effect. As for the functions \( K_{\sigma}, K_{\sigma D} \), with increasing the values \( \Delta h \), the influence of geometric parameters of elements on \( \tilde{\sigma}_R \) decreases (Figure 2e).

Summary

A comprehensive analysis of the previously conducted studies on the SPD influence on the structural elements and components’ fatigue strength has been carried out. The classification of these works according to SPD, geometric and contour parameters of the elements, the state of surface layers is carried out, and database on the fatigue resistance factors and indicators’ parameters has been composed.

For optimal assessment of the factors’ influence, a generalized mathematical SPD model is composed in the form of a multiparametric functional dependence, which for practical purposes is replaced by the parametric equations’ partial systems. The regression equations of these systems were obtained, which allows to get the whole set of optimal values of interrelated parameters without additional tests.

It is shown, that the identified functional relationships, which are particular mathematical models of SPD, confirm the improvement of the surface layers’ state and the machines strength rising. SPD effectively neutralizes the combined influence of the scale factor and stress concentration, approximating the values of \( \tilde{\sigma}_R \) closer to those for the flat samples.

The SPD influence on \( K_{d\sigma}, K_{\sigma}, K_{\sigma D} \) and \( \tilde{\sigma}_{R (V)} \), for different combinations of \( \Delta h, d, \tilde{\sigma}_\sigma \) priority parameters, which are proposed according to the design and operational regulations of the design structure, is considered. This makes possible to choose the optimal SPD parameters in the calculations, to specify the performance constructions’ indicators and to ensure their reliable and safer operation over the entire operation period.

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