Measures to Increase the Building Steel Structures’ Bearing Capacity

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Abstract. The issue of increasing the building structures steel elements’ bearing capacity using the surface plastic deformation (SPD) method, is considered, applying the complex assessment method of the factors’ parameters acting on the structure and fatigue resistance, which, in contrast to the current principle of differential evaluation, more accurately takes into account the structure’s state in the operating conditions. Interrelated functional dependencies between these indicators are identified and the parametric explanations’ systems taking into account the dominance of a certain factor in the design work, are made. These systems of equations make it possible to calculate the interrelated indicators and assess the impact of each of them on the structure’s bearing capacity.

1. Introduction

An expansive growth of the structural materials, various equipment and products’ manufacturing, the creation of new types of energy and information technologies, as well as the necessity of their implementation in production require to reduce the necessary financial expenses as much as possible. This approach assumes a systematization of the obtained results of the previously conducted large-scale experimental studies and measurements for a certain group of structural elements, identifying the multiparametric functional relationships and applying these results to obtain the optimal values of the bearing capacity criteria and the technological processes parameters, as a result of which it will be possible to reduce the designed structures’ costs.

These requirements put forward the necessity of each individual process’ improvement in the structures’ development and implementation, among which the processes of critical structural elements’ final processing are highlighted, which forms the necessary productivity indicators of the elements’ working surfaces. One of the relatively simple and effective methods for optimizing the physical and mechanical parameters of the surface layers is to increase the layers’ strength by the surface-plastic deformation (SPD) technological actions due to which the necessary irregularities of working surfaces are formed in the presence of a deformed layer and the appearance of residual compressive stresses, the static and dynamic strength of elements, as well as the surface wear resistance [1-4].

2. Methods

A significant variety of influencing factors and the combination of their possible options, considerable variation ranges of these factors’ parameters, as well as the bearing capacity of structural elements
needed to be selected and quantifying the optimal strengthening technology, require a classification of technical systems in this area, as well as the mechanisms’ structure adjustment, structural elements and materials used, the most prone to breakdown and failures [5-8].

In [7-11] the factors influencing the change in the physical and mechanical state of the structural elements’ surface layers due to SPD and their combined effects in various combinations are classified, the total result of which is the bearing capacity of elements and nodes according to the observed criteria (strength, stiffness, heat-, wear-, vibration resistance, etc.).

A comprehensive study of these processes in different combinations, as well as taking priority of one of them, when designing and manufacturing the products in large batches, cause the necessity for mathematical simulation [12, 13] of these processes and optimizing the indicators of the measures under study. This gives an opportunity to pass from the accepted differential approach to a comprehensive and systematic method of monitoring these processes, to identify the functional relationships between their indicators, and to suggest the optimal hardening processes.

Such indicators are the coefficients \(K_{d\sigma}, K_{\sigma}, K_{\nu\sigma}, K_{dD}\), which represent the ratio of the endurance limits that characterize the initial state, and the influence of the factor in fatigue processes (geometric parameters \(d, l\), the degree of stress concentration \(\bar{\sigma}_\sigma\), \(\Delta h\) the thickness of the deformed layer, \(K_{dD} = \frac{K_{d\sigma}}{K_{\nu\sigma}}\), and \(\bar{\sigma}_R\) is the median limit of endurance, taking into account all these coefficients. The relationship between the indicators of these factors can be generally represented as a multiparametric function [14, 15]:

\[
\Phi_6[(\Delta h, d, \bar{\sigma}_\sigma), (K_{d\sigma}, K_{\sigma}, K_{\nu\sigma}, K_{dD}, \bar{\sigma}_R)] = 0, \tag{1}
\]

which is a mathematical model of the hardening process and is used in practical calculations in the form of the parametric regression equations’ systems. The expression (1) can be represented as two separate multiparametric functions, for each of which a separate system of parametric equations can be formed.

a) \(K_{d\sigma}, K_{\sigma}, K_{\nu\sigma}, K_{dD}, \bar{\sigma}_R\) are the separate connections with \(\Delta h, d, \bar{\sigma}_\sigma\) according to the influencing factors;

b) interdependent relations of the same values from \(\Delta h, d, \bar{\sigma}_\sigma\). For the case a) of the possible priority the factors are selected as follows:

1. \((\Delta h, d, \bar{\sigma}_\sigma)\), 2. \((d, \Delta h, \bar{\sigma}_\sigma)\), 3. \((\bar{\sigma}_\sigma, \Delta h, d)\), \(\tag{2}\)

which are of practical interest, and from a large number and various combinations of functions (1), those components that significantly affect the fatigue resistance of the elements were selected. As a result, we obtain three groups of functions that satisfy the quantitative assessment of the hardening result for the structural elements of any shape and size [14,15]:

\[
\begin{array}{llll}
I & II & III \\
\begin{align*}
K_{d\sigma} &= f_1(\Delta h, d, \bar{\sigma}_\sigma), \\
K_{\sigma} &= f_2(\Delta h, d, \bar{\sigma}_\sigma), \\
K_{\nu\sigma} &= f_3(\Delta h, d, \bar{\sigma}_\sigma), \\
K_{dD} &= f_4(\Delta h, d, \bar{\sigma}_\sigma), \\
\bar{\sigma}_R &= f_5(\Delta h, d, \bar{\sigma}_\sigma),
\end{align*}
\begin{align*}
K_{d\sigma} &= \varphi_1(d, \Delta h, \bar{\sigma}_\sigma), \\
K_{\sigma} &= \varphi_2(d, \Delta h, \bar{\sigma}_\sigma), \\
K_{\nu\sigma} &= \varphi_3(d, \Delta h, \bar{\sigma}_\sigma), \\
K_{dD} &= \varphi_4(d, \Delta h, \bar{\sigma}_\sigma), \\
\bar{\sigma}_R &= \varphi_5(d, \Delta h, \bar{\sigma}_\sigma),
\end{align*}
\begin{align*}
K_{d\sigma} &= \psi_1(\bar{\sigma}_\sigma, \Delta h, d), \\
K_{\sigma} &= \psi_2(\bar{\sigma}_\sigma, \Delta h, d), \\
K_{\nu\sigma} &= \psi_3(\bar{\sigma}_\sigma, \Delta h, d), \\
K_{dD} &= \psi_4(\bar{\sigma}_\sigma, \Delta h, d), \\
\bar{\sigma}_R &= \psi_5(\bar{\sigma}_\sigma, \Delta h, d),
\end{align*}
\]

Unlike (3), for the case b) the parametric functions’ system can be formed in two stages: first, the functional relationship of indicators \(K_{d\sigma}, K_{\sigma}, K_{\nu\sigma}, K_{dD}\) and \(\bar{\sigma}_R\) is taken into account from the values of the priority factors influencing the design, \(\Delta h, d, \bar{\sigma}_\sigma\) - as arguments, then the arguments change, and the subsequent functional relations as such are the coefficients \(K_{\sigma}\) and \(K_{dD}\), and these relationships
different combinations of $\Delta h, d, \bar{\sigma}_\sigma$ are already represented as the functions parameters depending on the priority of design requirements (fatigue, dimensions, contour changes). Thus, in the functions, a fourth value ($K_{d\sigma}$ or $K_{dD}$) is added as an argument.

Considering the coefficients $K_{d\sigma}, K_{d\sigma}, K_{d\sigma}, K_{d\sigma}$ and $\bar{\sigma}_R$ in a logical sequence ($K_{d\sigma} - K_{d\sigma} - K_{d\sigma} - \bar{\sigma}_R$) dictates the interrelated functions’ representation of these quantities in I...IV quadrants of the coordinate system $(x, y)$. Based on these considerations, for the cases observed in (3), the new systems of parametric functions get the following form [14-17]:

\[ \begin{align*}
IV & \quad 1. K_{d\sigma} = f_1(\Delta h, d, \bar{\sigma}_\sigma), & x = \Delta h, \\
& \quad 2. K_{d\sigma} = f_2(K_{d\sigma}, d, \bar{\sigma}_\sigma), & x = K_{d\sigma}, \\
& \quad 3. K_{d\sigma} = f_3(K_{d\sigma}, \Delta h, d, \bar{\sigma}_\sigma), & x = K_{d\sigma}, \\
& \quad 4. K_{d\sigma} = f_4(K_{d\sigma}, d, \Delta h, d, \bar{\sigma}_\sigma), & x = K_{d\sigma}, \\
& \quad 5. \bar{\sigma}_R = f_5(K_{d\sigma}, d, \Delta h, d, \bar{\sigma}_\sigma), & x = K_{d\sigma}, \\
V & \quad 6. K_{d\sigma} = \varphi_1(d, \Delta h, \bar{\sigma}_\sigma), & x = d, \\
& \quad 7. K_{d\sigma} = \Phi_2(K_{d\sigma}, d, \Delta h, \bar{\sigma}_\sigma), & x = K_{d\sigma}, \\
& \quad 8. K_{d\sigma} = \Phi_3(K_{d\sigma}, d, \Delta h, \bar{\sigma}_\sigma), & x = K_{d\sigma}, \\
& \quad 9. K_{d\sigma} = \Phi_4(K_{d\sigma}, d, \Delta h, \bar{\sigma}_\sigma), & x = K_{d\sigma}, \\
VI & \quad 10. \bar{\sigma}_R = \Phi_5(K_{d\sigma}, d, \Delta h, \bar{\sigma}_\sigma), & x = K_{d\sigma}, \\
11. K_{d\sigma} = \psi_1(\bar{\sigma}_\sigma, d, \Delta h), & x = \bar{\sigma}_\sigma, \\
12. K_{d\sigma} = \Psi_2(K_{d\sigma}, \bar{\sigma}_\sigma, d, \Delta h), & x = K_{d\sigma}, \\
13. K_{d\sigma} = \Psi_3(K_{d\sigma}, \bar{\sigma}_\sigma, d, \Delta h), & x = K_{d\sigma}, \\
14. K_{d\sigma} = \Psi_4(K_{d\sigma}, \bar{\sigma}_\sigma, d, \Delta h), & x = K_{d\sigma}, \\
15. \bar{\sigma}_R = \Psi_5(K_{d\sigma}, \bar{\sigma}_\sigma, d, \Delta h), & x = K_{d\sigma}.
\end{align*} \]

3. Results

In the paper, for a comprehensive assessment of the geometric parameters’ influence on the reinforced structural elements’ bearing capacity, the influence analysis of the diameter size $d$ on the type and nature of changes in the functions of group II from (3) is given (Figure). Using modern technical computing system (Wolfram Mathematica and others), the regression equations in the form of $1\cdots3$ exponent power functions ($R^2 > 0.9$) were obtained for the computational and graphical estimation of these values. Since the paper considers the quantitative assessment of hardening under the combined influence of various factors as the main problem, the calculated points of the parametric functions (3) correspond to the values of the main factor $\Delta h = 0, 0.05, 0.10$ and $0.15mm$. As a result, for each parametric function (3), taking into account all the factors, 64 calculation points are obtained, which are 4 pieces grouped in 16 different subgroups, for which the regression equations are calculated in the same quantity.

As an example, these equations for the $\bar{\sigma}_R = \varphi_3(d, \Delta h, \bar{\sigma}_\sigma)$ function are presented in the Table. As the geometric parameters of the structural elements increase, the character of the curves $K_{d\sigma} = \varphi_3(d, \Delta h, \bar{\sigma}_\sigma)$ becomes descending with a decrease in their gradients, and this is more clearly shown for the flat elements ($\bar{\sigma}_{\sigma1} = 1$). The use of SPD ($\Delta h = 0.15mm$) increases the values of $K_{d\sigma}$ to 0.87...0.97, and at moderate stress concentrations – up to $K_{d\sigma} \approx 1.0$. 

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Figure 1. Changes in the function $\tilde{\sigma}_R = \varphi_5(d, \Delta h, \tilde{\sigma}_\sigma)$. Side notations: $(1_1, ..., 1_4)$ – $\tilde{\alpha}_{\sigma 1} = 1$; $(2_1, ..., 2_4)$, $(3_1, ..., 3_4)$, $(4_1, ..., 4_4)$ – are the elements with $\tilde{\alpha}_{\sigma 2}$, $\tilde{\alpha}_{\sigma 3}$, $\tilde{\alpha}_{\sigma 4}$. The indexes 1, ..., 4 correspond to $\Delta h = 0, 0.05, 0.10$ and 0.15 mm.

For the medium-carbon structural elements installed in power units of the medium-power process equipment ($d = 25...50$ mm) the above-mentioned coefficients vary within the following limits: $K_{d\sigma} = 0.88 \cdots 0.78, K_{\sigma} = 1.55 \cdots 2.60, r/d = 0.1 \cdots 0.025, K_{v\sigma} = 1.0 \cdots 1.9$ [16].

Table 1. The regression equations of the $\tilde{\sigma}_R = \varphi_5(d, \Delta h, \tilde{\sigma}_\sigma)$ function.

| N  | $\tilde{\alpha}_{\sigma i}$ | $\Delta h$, [mm] | $\tilde{\sigma}_R = \varphi_5(d)$ regression equations, $\Delta h = 0 \cdots 0.15$ mm, $\tilde{\alpha}_{\sigma 1}, \cdots, \tilde{\alpha}_{\sigma 4}$, ($x = d$) | $R^2$ |
|----|-----------------|-----------------|-------------------------------------------------------------------------------------------------|------|
| 1  | $\tilde{\alpha}_{\sigma 1}$ (plane, 1.00) | 0               | $\tilde{\sigma}_R = 3.75x^2 - 46.85x + 488.7$                                             | 0.997|
| 2  |                 | 0.05            | $\tilde{\sigma}_R = 2.50x^2 - 33.90x + 482.5$                                             | 0.989|
| 3  |                 | 0.10            | $\tilde{\sigma}_R = 3.50x^2 - 36.90x + 507.5$                                             | 0.999|
| 4  |                 | 0.15            | $\tilde{\sigma}_R = 5.50x^2 - 44.10x + 548.5$                                             | 0.999|
| 5  | $\tilde{\alpha}_{\sigma 2}, 1.25$ | 0               | $\tilde{\sigma}_R = 3.25x^2 - 29.79x + 332.2$                                             | 0.988|
| 6  |                 | 0.05            | $\tilde{\sigma}_R = 0.25x^2 - 6.95x + 368.7$                                             | 0.999|
| 7  |                 | 0.10            | $\tilde{\sigma}_R = 0.75x^2 - 7.65x + 373.2$                                             | 0.969|
| 8  |                 | 0.15            | $\tilde{\sigma}_R = 0.75x^2 - 9.05x + 389.2$                                             | 0.999|
| 9  | $\tilde{\alpha}_{\sigma 3}, 1.75$ | 0               | $\tilde{\sigma}_R = 225x^2 - 25.95x + 289.2$                                             | 0.994|
| 10 |                 | 0.05            | $\tilde{\sigma}_R = 0.50x^2 - 8.70x + 342.5$                                             | 0.990|
| 11 |                 | 0.10            | $\tilde{\sigma}_R = 2.75x^2 - 22.65x + 375.2$                                             | 0.994|
| 12 |                 | 0.15            | $\tilde{\sigma}_R = 2.50x^2 - 19.90x + 393.5$                                             | 0.999|
| 13 | $\tilde{\alpha}_{\sigma 4}, 2.78$ | 0               | $\tilde{\sigma}_R = 1.75x^2 - 18.65x + 191.2$                                             | 0.995|
| 14 |                 | 0.05            | $\tilde{\sigma}_R = 1.50x^2 - 17.30x + 256.5$                                             | 0.980|
| 15 |                 | 0.10            | $\tilde{\sigma}_R = 2.00x^2 - 18.40x + 271.5$                                             | 0.999|
For the function $\varphi_2(d, \Delta h, \tilde{\sigma})$ the diametral parameter $d$ influence is insignificant and the degree of stress co-concentration plays the main role on the value $K_\sigma$. However, the surface layers’ elements hardening for the considered types of concentrators reduces the effect of stress concentration by up to 42% due to the occurrence of residual compressive stresses on the elements’ surface layers.

The total coefficient function of the factors’ influence $K_{\sigma D} = \varphi_4(d, \Delta h, \tilde{\sigma})$ mainly depends on the values $K_\sigma$ and $K_{\sigma D}$, or rather – on $K_{\sigma D}$, which forms a gradient and interval of values of $K_{\sigma D}$.

At $\Delta h = 0.15 \text{ mm}$ and $\tilde{\sigma}_{aD} = 2.75$ the values $K_{\sigma D}$ reach up to $K_{\sigma D} \approx 3.00$, which significantly increases the structural elements’ bearing capacity.

For the observed ranges of the parameters $d, \Delta h, \tilde{\sigma}$, the values of the hardening coefficient $K_{\sigma a} = 1.20 \cdots 1.79$ are neutralizing the factors: geometric and stress concentrations, and in some cases even provide the condition $\tilde{\sigma}_R > \tilde{\sigma}_R 0 (\tilde{\sigma}_R 0$ – the limit of a laboratory sample’s endurance with $d 0 = 7.5 \cdots 10.0 \text{ mm}$), which not only indicates a mutual balance of these factors’ influence, but also in the case of some hardening technological modes - the exceeding of the structural elements’ endurance limits from the initial values of these limits (Fig.). For the plane elements ($\tilde{\sigma}_a=1.00$), due to the geometric parameters’ growth, the reduction of the endurance limit $\tilde{\sigma}_R$ reaches up to 23%, and the slope $\Delta h=0.15 \text{ mm}$ provides not only the restoration of the value of $\tilde{\sigma}_R$, but also growth within 10...13%. This phenomenon is most pronounced at the medium levels of stress concentration ($\tilde{\sigma}_a=1.25 \cdots 1.75$).

If the limit of the non-reinforced elements’ endurance is reduced by 46 ... 95%, then when hardening ($\Delta h = 0.15 \text{ mm}$), it is restored and 8...13% higher than the original data. At a high level of stress concentration ($\tilde{\sigma}_a=2.75$), the drop $\tilde{\sigma}_R$ of the non-reinforced elements is significantly -156...200%, which leads to the mandatory use of hardening technology to ensure the necessary degree of bearing capacity of these nodes. According to the data, in the case of $\Delta h=0.15 \text{ mm}$, this drop decreases and reaches up to 6 ... 14%, and in the case of $\Delta h > 0.15 \text{ mm}$, even exceeding the initial data is possible (Figure).

4. Summary
The complex analysis of main factors affecting the structure’s bearing capacity (dimensions and contour shape, stress concentration, surface hardening) is carried out in case of the priority effects of each of them. Considering the presence of various factors affecting the processes under study in various combinations, a method of system analysis was applied, according to which the most practical options were classified and selected, for which the multiparametric functional relationships were obtained and a common mathematical model of the hardening process was proposed, which allows choosing the optimal technological parameters of this process. Mutual functional relationships between the fatigue strength coefficients ($K_{d0}, K_\sigma, K_{\sigma D}$), the endurance limits $\tilde{\sigma}_R$ and $d, \Delta h, \tilde{\sigma}$ parameters used in the bearing capacity calculations are obtained [18], which allows determining the optimal values of these coefficients, $\tilde{\sigma}_R$ and the parameters for various combinations of sequential factors in practical calculations.

Acknowledgements
This work has been carried out in the frame of “Creating the ways for sustainable urban, architectural and construction complexes development in Republic of Armenia and elaboration of directions with use of permanent monitoring system” programme, financed by Science Committee of Republic of Armenia.

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