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Fundamentals of Stable Drawing Process of Steel Rod, Which Has Integrity Violations

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Using the developed method, the deformation regularities of artificial cone-shaped defects' models on wire rod and wire during their multiple drawing are experimentally determined for the first time. As found, for the most part, the smoothing of such defects occurs more intensively, the greater the total wire elongation and the initial values of the depth and width of the defects. These data are compared with the results of the previous similar investigations on wire deformation in the presence of defects of predominantly transverse orientation and predominantly longitudinal one relative to the drawing axis. As shown, the qualitatively obtained new results are closer to the 'transverse' defects' deformation patterns, and the quantitative differences can be explained by the presence of a volumetric scheme of the metal stress-strain state around the artificial surface violation of its continuity. The influence of the presence of such artificial formations ('defects') on the condition of uninterrupted wire drawing is determined. Attention is paid to the possible additional negative influence of 'defects' as stress concentrators on the stability of the drawing process. The results of the investigation may be useful in designing the routes for continuous multiple drawing of a work-piece with the probable presence of continuity defects on it, and in investigating the mechanism of deformation of such surface defects to obtain drawn wire of acceptable quality. A promising direction of research is to combine

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the data of existing work with known methods for calculating force conditions of deformation and thoroughly quantifying the parameters of designed routes for multiple stable wire drawing.

Key words: drawing, wire rod, wire, surface defects, deformation regularities.

З використанням розробленого методу уперше експериментально визначено закономірності деформування штучних моделей конусоподібних дефектів на катанці та дроті за їхнього багаторазового волочіння. Виявлено, що здебільшого має місце вигладжування таких дефектів тим інтенсивніше, чим більше сумарна витяжка дроту та початкові значення глибини та ширини дефектів. Дані зіставлено з результатами попередніх аналогічних досліджень під час деформування дроту за наявності на ньому дефектів переважно поперечної та переважно поздовжньої орієнтації відносно осі волочіння. Показано, що якісно одержані нові результати ближче до закономірностей деформування «поперечних» дефектів, а кількісні відмінності можуть бути пояснені наявністю об'ємної схеми напружено-деформованого стану металу в околі штучного поверхневого порушення його суцільності. Визначено вплив наявності таких штучних утворень («дефектів») на умову безобривного волочіння дроту. Приділено увагу щодо наявності вірогідного додаткового негативного впливу «дефектів» як концентраторів напружень на стабільність процесу волочіння. Результати дослідження можуть бути корисними під час проєктування маршрутів безобривного багаторазового волочіння заготовки з вірогідною наявністю на ній дефектів суцільності, для вивчення механізму деформування таких поверхневих дефектів з одержанням волоченого дроту прийнятної якості. Перспективним напрямом досліджень представляється об'єднання даних даної роботи з відомими методиками розрахунку силових умов деформування та ґрунтового кількісного визначення параметрів проєктованих маршрутів багаторазового стабільного волочіння дроту.

Ключові слова: волочіння, катанка, дріт, поверхневі дефекти, закономірності деформування.

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1. INTRODUCTION

Drawing as a method of metal forming by pressure consists of one or more times pulling a previously rolled or pressed workpiece through the drawing die hole. The die cross-sectional area is smaller than the workpiece cross-sectional area, and its configuration forms a given profile of the product: wire, thin-walled pipe, round in cross-section or profiled shaped bar. As a result, the cross-sectional area of the metal decreases and the length of the product increases.

As an initial workpiece for the production of cold-drawn steel wire with a final diameter of $d_e = 0.002\text{--}6$ mm, a wire rod with a nominal diameter of $d_0 = 5.5\text{--}6.5$ mm is usually used. The workpiece for drawing

in subsequent drawing cycles is the wire obtained after the previous passes.

The possibility of the process is assessed by the value of the safety factor coefficient, which is determined by the ratio of the wire tensile strength and the tensile stress ('drawing stress') at the drawing die exit, and which must be no less than a certain critical value of $[\gamma] = 1.34-2.10$ [1]:

$$\gamma = \sigma_{B1} / \sigma \geq [\gamma]. \quad (1)$$

The variation range of $[\gamma] = 1.34-2.10$ was determined experimentally for a standard workpiece, which is due to factors that destabilize the values of σ_{B1} and σ , and its smaller value corresponds to a larger wire diameter.

These force parameters are formed by the conditions in different sections of the deformation zone of die and depend on the metal strengthening, which is due to its chemical composition and the accumulated elongation μ_Σ while drawing [1]:

$$\mu_\Sigma = F_0 / F_{1n} = \prod_{i=1}^n \mu_i, \quad (2)$$

where F_0 , F_{1i} are the area of the initial and at the exit from the n -th drawing metal cross-section, n is the drawing multiplicity ($1 \leq i \leq n$), the drawing elongation in the i -th pass [1]:

$$\mu_i = F_{0i} / F_{1i}, \quad (3)$$

F_{0i} is the area of metal at the entrance of i -th die.

It is clear that for round cross-sections of wire rod and wire: $F_0 = \pi d_0^2 / 4$, $F_{0i} = \pi d_{0i}^2 / 4$, $F_{1i} = \pi d_{1i}^2 / 4$ (where d is the corresponding diameter). In addition, the drawing stress σ depends on the friction conditions and the geometry of the drawing.

Using the levels σ_{B1} and $[\gamma]$ according to (1) it is possible to obtain the value σ , and then by reverse calculation using one of the numerous known formulas [1, 2, 3, *etc.*] taking into account the dependence of the mechanical properties of the metal on μ_Σ , the geometry of the die and the friction conditions, determine the characteristics of the metal compression in the drawing, in particular μ_Σ , and also (if necessary)—the mode of multiple drawing. The value μ_i usually ranges from 1.05 to 1.5.

The main regulatory documents regulating the quality of steel wire rod are the standards: European EN 16120 (in four parts), American ASTM A510/A510M, Ukrainian ДСТУ 2770, ДСТУ 2651, ДСТУ 4738, ДСТУ 3684, Technical conditions of Ukraine ТУ У 27.1-00190319-1280, ТУ У 27.1-00190319-1314, *etc.* [4].

Such production in Ukraine is carried out at several large enterpris-

es (PJSC ‘Zaporizhzhia Steel Rolling Plant’, LLC ‘Dniprometiz TAS’, PJSC ‘Stalakanat’, LLC ‘Garant Metiz Invest’ [5] and at several dozen smaller firms.

The annual output of drawn steel wire in Ukraine and, accordingly, wire rod in the period 2015–2021 was 270–380 thousand tons, which is approximately 8–10% of the rolled products amount. The market value of steel wire is 21–24 thousand UAH per ton [6].

After the ^{Russian} invasion of Ukraine and the loss of control over some metallurgical enterprises, such production decreased by 15–35%. More accurate data (according to the Law of Ukraine ‘On Official Statistics’ of August 16, 2022, No. 2524-IX) are classified as confidential statistical information [7, 8].

Drawn steel wire is used to make ‘hardware’—metal products that are mostly used to fasten steel, wooden and plastic parts or components, and are also used for household purposes as tools [9].

In the production practice of hardware enterprises (drawing, mesh, electrode, nail, fastening, *etc.* shops of metallurgical enterprises), such products include mesh, cables, electrodes, ropes, bolts, screws, nuts, nails, cotter pins, *etc.*

The approximate structure of steel wire mass consumption is as follows: commercial wire of various general purposes—up to 59%, cables and ropes—10%, wire for reinforcing reinforced concrete structures—7%, nails and other fasteners—more than 5%, fibre—4%, steel mesh—3%, *etc.* [5].

2. ANALYSIS OF THE PROBLEM

Although each of the above-mentioned types of products has specific requirements, which are reflected in a large number of standards [10], manufacturers often use the cheapest low-carbon wire rod when manufacturing wire and hardware for general (non-responsible) purposes. The latter may have an expanded (compared to standards) range of variation of geometric and mechanical characteristics, as well as minor surface and volumetric defects that do not prevent its further use for its intended purpose. An example may be binding wire, nails, *etc.*

Production experience shows that defects (with typical sizes from fractions of a μm to several mm) and their location in the volume and (or) on the surface of the workpiece can significantly negatively affect the stability of the drawing process, causing breaks, premature failure of dies, *etc.* At the same time, such an impact is greater the more: the ratio of the defect sizes to the cross-sectional dimensions of the workpiece and wire [11], the difference between the strength properties of the base metal and the material of the defect itself [11].

Defective wire rod accounts for approximately 10% of its total output and is delivered in coils, which makes it difficult to identify devia-

tions from regulatory requirements. In fact, it should be scrapped with losses of the difference in the corresponding prices. At the same time, the price of scrap metal is 5–10 times lower than the price of standard wire rod, and the corresponding losses, in fact, are borne usually by the hardware company.

The standardization of the use of such a workpiece in practice is carried out by adopting specifications and (or) technical conditions for the workpiece and products made from it, agreed between the parties, with a corresponding price reduction.

Therefore, it becomes economically feasible to develop measures to ensure stable drawing of wire rod, which has non-critical deviations from the requirements of the standard, which do not prevent the production of high-quality final products. This has led to the feasibility of investigating the deformation patterns not only of the workpiece itself, but also of defects that may occur on it, as well as their impact on the stability of the drawing process.

Usually, fixing and identifying the type and size of specific defects is possible only on samples specially selected from the beginning or end of the wire rod coil, or in places of wire breaks (in case of violation of stable drawing regimes). Based on the number of detected violations, an expert conclusion is made on the possibility and feasibility of processing such wire rod into conditioned wire without changing the established deformation regime, and subsequently for the manufacture of hardware.

Nevertheless, at the same time, continuous drawing with regulated reduced compression of the workpiece must be ensured, usually in several passes to achieve the required wire size.

Obviously, this is ensured by defining μ_i , when performing, a relation similar to formula (1) [11]:

$$\gamma = \sigma_{B1} / \sigma \geq K_{\text{def}} [\gamma], \quad (4)$$

where $K_{\text{def}} (> 1)$ is the coefficient of the defect influence on the conditions of stable (continuous) drawing.

The quantitative assessment K_{def} in the investigation [11] took into account the following: the presence of a defect with K_{def} cross-sectional area (relative to the workpiece axis) reduces the area of defect-free metal compared to the area F_{1i} at the exit from the drawing die, as well as the strength of the wire regardless of the material strength that fills the volume of the defect and does not resist stretching due to a violation of the continuity of the material of the entire product; the drawing process destabilizes precisely the difference in strength $\sigma_{B,\text{def}}$ of the material filling the defect from σ_{B1} the base metal of the wire, since the latter depends on the total μ_Σ (2) and partial μ_i (3) drawing elongation.

Then, to ensure $K_{\text{def}} > 1$, this parameter was defined [11]: when

$\sigma_{B,def} \leq \sigma_{B1}$ according to the formula [11]:

$$K_{def,i} = \frac{F_{1i} \sigma_{B1}}{(F_{1i} - F_{def}) \sigma_{B1} + F_{def} \sigma_{B,def}} > 1, \quad (5)$$

when $\sigma_{B,def} \geq \sigma_{B1}$ according to the formula [11]:

$$K_{def,i} = \frac{(F_{1i} - F_{def}) \sigma_{B1} + F_{def} \sigma_{B,def}}{F_{1i} \sigma_{B1}} > 1. \quad (6)$$

Usually, as a result of preparing the workpiece for drawing by etching or alternating bending, its surface defects become hollow ($\sigma_{B,def} \rightarrow 0$). Then, from Eq. (5), it followed [11]:

$$K_{CID,i} = \frac{F_{1i}}{F_{1i} - F_{def,i}} > 1, \quad K_{def,i} = \frac{F_{1i}}{(F_{1i} - F_{def})} > 1, \quad (7)$$

and to determine the value K_{def} according to formulas (5)–(7), quantitative data on the regularities of the shape change of defects during the drawing process, taking into account their initial shape and location in the body of the workpiece relative to the axis of the latter, became necessary.

The shape, size, and location of defects in a workpiece cannot be predicted a priori.

Therefore, theoretical assessment of their influence on the stability of the drawing process is possible only by investigating the deformation process of simplified defect models, and experimental assessment is possible by creating artificial ‘defects’ on the workpiece: drilling and surface notches with different geometry, dimensions and orientation, followed by deformation, measurement of dimensions and corresponding analysis of the results.

The first logical step towards developing appropriate measures was to identify the most common defects in wire rod. These include [11–15, *etc.*]:

- non-metallic (oxide, slag) inclusion in the volume or (and) on the surface of the wire rod; the consequence of the presence of such a volumetric defect is the formation of discontinuity and (or) heterogeneity of the properties of the workpiece material, and the surface violation of the continuity of the metal, as a rule, exfoliates during the deformation process and leaves behind a shell with a depth of fractions of a millimetres to a through hole;
- delamination, which can originate during preliminary rolling, appear during deformation of wire rod areas with the presence of non-metallic inclusions or shrinkage, or serious segregation by chemical composition, which causes excessive internal stresses in the metal up to the appearance of cracks;

- longitudinal and transverse cracks, which may be the result of uneven deformation of the metal in terms of volume with the initial presence of surface defects, microscopic pores and bubbles, or overburning during preliminary heat treatment;
- delaminations ('captures'), which are a consequence of the loss of radial stability and subsequent rolling of the surface convexities of the workpiece during its deformation, and which, as a rule, turn into delamination or cracking during drawing;
- scratches and dents of different depths and directions relative to the wire rod axis, *etc.*

Given that the present work is a continuation of previous similar investigations under the same leadership, it became appropriate to make a certain generalization and analysis of the results already obtained. The emphasis is placed on the fact that in the deformation centre during wire drawing in the radial direction to its axis, compressive stresses and strains act, and in the longitudinal direction—tensile.

Such a scheme of the stress-strain metal state is dangerous from the point of view of initiating wire breakage under the action of the drawing force, especially in the presence and influence of wire continuity violations along the drawing axis [1]. In this case, the dimensions of these violations in the cross section perpendicular to the drawing axis (wire) must be taken into account.

As a part of the research conducted earlier and reflected in the works [16, 17], results were presented regarding the deformation patterns of one type of artificial defects.

In particular, in work [16], the deformation zone during drawing was theoretically considered with a defect model in the form of a through cylindrical drilling with a diameter of Δ_0 , located transversely to the axis of a round wire rod with a diameter of d_0 . Virtual 'deformation' occurred in a conical drawing die with a drawing elongation μ_i , and the metal received a total drawing elongation $\mu_{\Sigma i}$ at the exit from the sequence of draws, starting from the first one.

This model of a conditional 'defect' was presented: hollow with a tensile strength $\sigma_{B,def} = 0$, filled with a material with a tensile strength lower than that of the base metal ($\sigma_{B,def} < \sigma_{B1}$), filled with a material with a tensile strength close to the base metal ($\sigma_{B,def} \approx \sigma_{B1}$), filled with a material with a tensile strength greater than that of the base metal ($\sigma_{B,def} > \sigma_{B1}$).

During the theoretical analysis, the authors took into account that the wire rod (preform) during drawing is stretched along the longitudinal axis z and compressed radially along the axis ρ . This caused the deposition of the 'defect' along its 'height', which was equal to the current diameter d_{zi} in the drawing, and the initial circular cross-section of the 'defect' with a diameter Δ_0 acquired an elliptical shape with the current dimensions a_{zi} (along the metal axis) and b_{zi} (perpendicular to

the longitudinal axes of the wire and the ‘defect’ model).

Based on reasonable assumptions about the invariance of the cross-section of the ‘defect’ during metal deformation i -th gap [16] and the relationship between deformations and stresses [1], it was shown that for an arbitrary ratio $(\sigma_{B,def}/\sigma_{B1i})$ [16]:

$$b_{Zi} = \frac{\Delta_{Zi}}{1 - (\sigma_{B,def}/\sigma_{B1i})(\Delta_{Zi}/d_{Zi}) + \Delta_{Zi}/d_{Zi}}, \quad (8)$$

$$a_{Zi} = \frac{\Delta_0 \sqrt[4]{\mu_{\Sigma i}} [d_{Zi} + (1 - \sigma_{B,def}/\sigma_{B1i})\Delta_0 \sqrt[4]{\mu_{Zi}}]}{d_{Zi}} \left[1 + \frac{\Delta_0 \sqrt[4]{\mu_{Zi}}}{2(d_{Zi} - (\sigma_{B,def}/\sigma_{B1i})\Delta_0 \sqrt[4]{\mu_{Zi}})} \right]. \quad (9)$$

For the cross section of the metal exit and the ‘defect’ from the deformation centre, according to Eqs. (8) and (9), as well as formulas (2) and (5) from the source [16]:

$$\Delta_{1i} = \Delta_0 \sqrt{\mu_{\Sigma i}}, \quad (10)$$

after transformations, taking into account $F_0 = \pi d_0^2/4$, $F_{0i} = \pi d_{0i}^2/4$, $F_{1i} = \pi d_{1i}^2/4$, it turned out [16] with $d_{Zi} = d_{1i} = d_{0i}/\sqrt{\mu_{\Sigma i}}$ and arbitrary ratio $\sigma_{B,def}/\sigma_{B1i}$ [16]:

$$b_{Zi} = \frac{\Delta_0 \sqrt{\mu_{\Sigma i}}}{1 - (\sigma_{B,def}/\sigma_{B1i})(\Delta_0 \mu_{\Sigma i}/d_0) + \Delta_0 \mu_{\Sigma i}/d_0}, \quad (11)$$

$$a_{Zi} = \frac{\Delta_0 \sqrt[4]{\mu_{\Sigma i}} [d_0 + (1 - \sigma_{B,def}/\sigma_{B1i})\Delta_0 \mu_{\Sigma i} \sqrt{\mu_{\Sigma i}}]}{d_0} \left[1 + \frac{\Delta_0 \mu_{\Sigma i} \sqrt{\mu_{\Sigma i}}}{2(d_0 - (\sigma_{B,def}/\sigma_{B1i})\Delta_0 \mu_{\Sigma i} \sqrt{\mu_{\Sigma i}})} \right]; \quad (12)$$

with $\sigma_{B,def}/\sigma_{B1i} = 0$,

$$b_{1,0,i} = \Delta_0 d_0 \sqrt{\mu_{\Sigma i}} / (d_0 + \Delta_0 \mu_{\Sigma i}), \quad (13)$$

$$a_{1,0,i} = \Delta_0 \sqrt[4]{\mu_{\Sigma i}} [1 + \Delta_0 \mu_{\Sigma i} \sqrt{\mu_{\Sigma i}} / 2d_0]; \quad (14)$$

with $\sigma_{B,def}/\sigma_{B1i} = 1$,

$$b_{1,1,i} = \Delta_0 \sqrt{\mu_{\Sigma i}}, \quad (15)$$

$$a_{1,1,i} = \Delta_0 \sqrt[4]{\mu_{\Sigma i}} \left[1 + \frac{\Delta_0 \mu_{\Sigma i} \sqrt{\mu_{\Sigma i}}}{2 \cdot (d_0 - \Delta_0 \mu_{\Sigma i} \sqrt{\mu_{\Sigma i}})} \right]. \quad (16)$$

The results of calculations using formulas (11)–(13) were compared with experimental data [17].

In those experimental investigations, defect modelling was carried out by through-hole drilling with a diameter of $\Delta_0 = 2.0, 1.5$ and 1.0 mm perpendicular to the axis of the wire rod, which had a diameter of

$d_0 = 6.50$ mm. Modelling of the material properties of defects was performed using the following options: filled with rods made of aluminium, unhardened and pre-hardened low-carbon steel with known tensile strength values, as well as without filler.

The wire rod with holes was drawn through double dies in one pass to a diameter of $d_1 = 6.2$ mm ($\mu_i = \mu_s = 1.048$) in the presence of dry soap lubricant. After that, cylindrical samples were cut from the wire at the locations of the deformed 'defects', cut along the axis, made longitudinal sections of them, and measured the dimensions of the hole with a trammel.

It was found that, after drawing the workpiece, the initial round cross-sectional shape of the drilling-'defect' transformed into an elliptical one with dimensions a and b .

Comparison of experimental (index 'exp') and theoretical (index 'theor') values a revealed their satisfactory coincidence with a deviation of no more than 25% and the feasibility a of introducing a correction empirical coefficient A , which approximated the results of calculations and experiments with a deviation of no worse than 1% in the form of [17]:

$$a_{1i,\text{theor}} = A a_{1i,\text{exp}}, \quad (17)$$

were

$$A = 1.24 - 1.50 \frac{\Delta_0}{d_1} + 0.070 \frac{\sigma_{B,\text{def}}}{\sigma_{B \text{ Me.}}} + 0.25 \frac{\Delta_0}{d_1} \frac{\sigma_{B,\text{def}}}{\sigma_{B \text{ Me.}}}. \quad (18)$$

At the same time, the experimental data were more thorough.

At the analysis took into account that the cross section of the exit from the deformation zone and the deformation zone itself were at a certain distance from each other. As a result, if there is a 'defect' of a certain length a_i at the exit from the die, the metal in the deformation zone itself may not contain a defect. This situation is accompanied by a wire front end weakening and the preservation of the required drawing force.

What was important here it was that the size is 'responsible' for the weakening of the wire cross-section by the diameter d_{1i} at the exit from the drawing die in the presence of a defect according to Eq. (7) was precisely the size b_{1i} .

The data presented in Ref. [17] allowed us to assess the influence of the area of $F_{i,\text{def}} = b_{1i} d_{1i}$ a through-hole defect in the wire rod in the form of an initial cylindrical hole in the cross-section of the metal exit from the drawing die with the area $F_{1i} = \pi d_{1i}^2 / 4$ on the corresponding 'weakening' of the wire cross-section with a decrease in its reduced strength. In this case, it became possible to assume in a first approximation that the area of the conditionally cylindrical cross-section of the defect model with a diameter at the exit from the drawing is trans-

formed into an ellipse with axes a and b . From this, it follows: $\Delta_{1i}^2 = a_{1i} b_{1i}$ and $b_{1i} = \Delta_{1i}^2 / a_{1i}$.

Calculation of values $a_{1.0,i}$ according to formula (14) and adjustment of this quantity according to formulas (17) and (18) necessitated a corresponding change in the quantity b_i . Then, taking into account formula (10), after simple transformations, it is obtained [17]:

$$b_{1i} = \frac{\Delta_{0i}^2 \mu_{1i}}{A a_{1i, \text{theor}}}, \quad (19)$$

and it became appropriate to determine the defect influence coefficient K_{def} according to the simplified formula (7), which after simple transformations gave [17]:

$$K_{\text{def}} = \frac{\pi d_{1i}^2}{\pi d_{1i}^2 - 4 d_{1i} b_{1i}} > 1, \quad (20)$$

regulating according to (4) the corresponding reduction μ_i in the allowance.

Unlike volumetric defects, surface defects of a workpiece with different geometry and penetration depth (sometimes up to half its diameter), depending on the pressure treatment conditions, may disappear as a result of smoothing, remain or close, turning into a 'crack' [11].

To assess the influence of the size and orientation of surface defects on the results of their deformation and the conditions of stable multiple drawing of steel rod and wire, the results of relevant experimental investigations were presented using a specially developed method [11].

The drawing of prepared samples of wire rod with a diameter $d_0 = 6.5$ mm made of low-carbon steel was carried out through prefabricated double dies made of BK-6 alloy on a chain mill at a speed of 0.2 m/s for 4 passes along the corresponding routes: $6.2 \rightarrow 5.9 \rightarrow 5.45 \rightarrow 5.05$ mm (partial drawing elongation μ_i were $1.10 \rightarrow 1.10 \rightarrow 1.17 \rightarrow 1.16$).

Sodium soap powder was used as a technological lubricant.

On the surface of the workpiece, longitudinal and transverse (relative to the wire rod axis) notches with a depth $h_0 = 2.5, 1.6, 1.2$ and 1.0 mm and a size of $2.6\text{--}6.5$ mm in the direction perpendicular to the drawing axis were applied by milling. Another size of the notches was 1 mm. This was significant in the subsequent determination of the weakening of the wire profile at the exit from the drawing.

The notches were placed along the axis of the workpiece in 4 groups (according to the number of passes, respectively). The distance between the notches was at least of 10 mm, and between their groups, it was of 100 mm (Fig. 1) to prevent the mutual influence of these defect models during metal deformation.

From the wire rod and after each i -th pass from the wire rear end with a diameter d_{1i} , sections with a 'defects' group were cut off, then

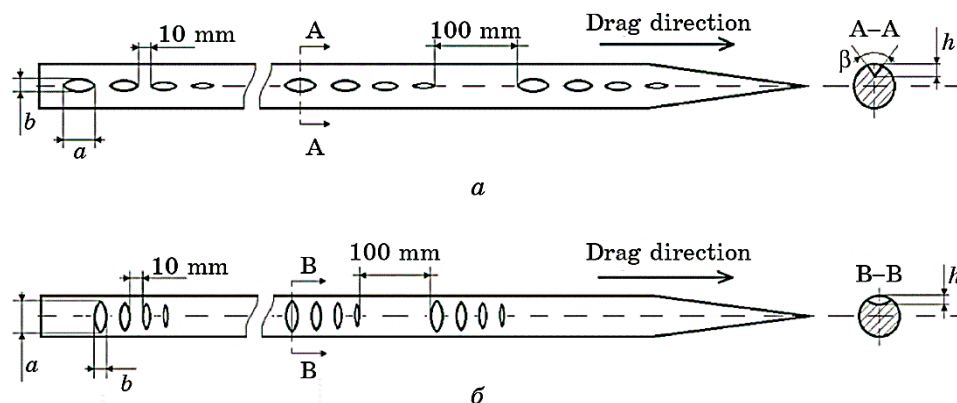


Fig. 1. Scheme of preparation of wire rod samples with groups of longitudinal (a) and transverse (b) surface notches (shown for three passes) [11].

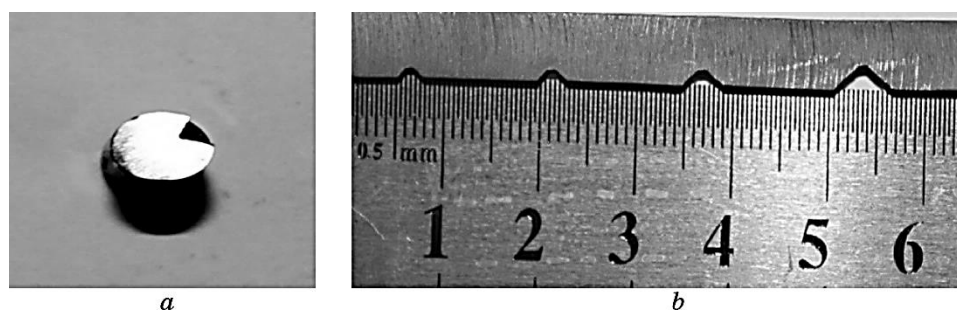


Fig. 2. Examples of deformed wire sections photographs: transverse with a longitudinal 'defect' applied (a), longitudinal with transverse 'defects' applied (in comparison with a fragment of the tool ruler) (b) [11].

each of them with the surrounding metal zone was separated, marked, cut at the place of their maximum depth and perpendicular to the wire axis, polished and photographed with a digital camera (Fig. 2).

The accuracy of such measurements was limited to visual determination of dimensions (within 0.5 mm). It became possible to increase the accuracy of measurements by transferring a digitized image of defects to a computer monitor screen.

The transition from enlarged computer images to the corresponding actual 'defects' sizes was carried out taking into account the 'conversion factor':

$$K_p = \frac{l_{\text{inst}}}{l_{\text{comp}}} < 1, \quad (21)$$

where l_{inst} , l_{comp} are respectively, the results of instrumental measure-

ment of the dimensions of the product in an accessible place (for example, the diameter d_0 of the wire rod using a micrometres with an accuracy of ± 0.01 mm) and measurements of the dimensions of the computer display of the same place using a tool ruler.

The regularities of deformation of surface defect models depending on the values of total drawing elongation $\mu_\Sigma = (d_0/d_i)^2$, drawing elongation $\mu_i = (d_{i-1}/d_i)^2$ in the i -th pass and (or) the corresponding change in the perimeter of the wire cross-section $\sqrt{\mu_i} = d_{i-1}/d_i$, as well as the number of compressions (passes) were judged by the change in the measured depth h and size b of the notch in the direction perpendicular to the drawing axis before (index ' $i-1$ ') and after (index ' i ') deformation in the pass (see cross-sections A-A and B-B in Fig. 1).

Accordingly, the ratio h_{i-1}/h_i reflected the intensity of the decrease in the depth of the 'defect' with increasing μ_Σ and μ_i ; an increase in the ratio $K_{1i} = b_{1i}/h_{1i}$ corresponded to the relative expansion (smoothing) of the 'defect', and a decrease K_{1i} —to its narrowing, *i.e.* the tendency to transform the notch into a longitudinal 'crack') after drawing in the next i -th pass. The ratio $K_{2i} = b_i d_{i-1}/(b_{i-1} d_i)$ also assessed the synchronicity of the change in the width of the 'defect' and the perimeter (diameter) of the wire. The value $K_{2i} = 1$ corresponded to the synchronous change in the width of the 'defect' and the perimeter of the product; the value $K_{2i} < 1$ corresponded to the tendency to transform the notch into a longitudinal 'crack', and $K_{2i} > 1$ —to the tendency to smooth the 'defect' relative to the perimeter (diameter) of the wire, which decreased in successive drawing passes. Additionally, it was possible to estimate the angle at the apex of the notch: $\beta = 2\arctg(b_i/2h_i)$ (Fig. 1).

The results obtained in the investigation [11] indicated the following.

With a longitudinal (relative to the workpiece axis) orientation of the notches (see Fig. 1, *a*), with increase μ_Σ the depth h_i and width b_i of the 'defect' decreased intensively, mainly in the first two passes, the more so, the larger their initial values were h_0 and b_0 on the wire rod, and then at $\mu_\Sigma > 1.2$ – 1.4 the intensity of their change decreased, and they asymptotically approached in magnitude.

Important here was the decrease in the magnitude K_{1i} and corresponding angle β_i with increasing extraction μ_Σ , which indicated a tendency for such a 'defect' to transform into a longitudinal 'crack' the more intense the greater the extraction μ_Σ and the smaller the initial depth h_0 of the 'defect'.

The non-monotonic nature of the change $K_{2i \text{ prod}} < 1$ from μ_Σ in the longitudinal orientation of the defects reflected the complex influence of strengthening and the stress state scheme of the metal in the deformation centre near the notch during wire deformation and, in general, confirmed the tendency for the longitudinal notch to transform into a 'crack'. This dependence was probably due to the complex influence of

the metal deformation conditions on the metal flow.

With the transverse orientation of the notches on the workpiece relative to the axis (see Fig. 1, *b*), a monotonic decrease in the depth h_i and width b_i of the ‘defects’ was also observed with the increase in μ_Σ . But in this case, the magnitude K_{1i} and the corresponding angle β_i values increased, which indicated a tendency to smooth out such ‘defects’. This was also consistent with the values $h_{i-1}/h_i > 1$ in the entire investigated range of the increase in the parameter $\sqrt{\mu_i} = d_{i-1}/d_i$. In this case, a more intensive smoothing of the transverse ‘defect’ became important in comparison with the decrease in the wire cross-sectional perimeter.

Also, in Ref. [11], the influence of surface defects of longitudinal and transverse orientation relative to the wire axis on the stability of the drawing process in the i -th passes was estimated using geometric relations by the coefficient value according to formula (7).

Accordingly, for the longitudinal orientation of the defect when considering the method of notches applying to the workpiece, its cross-sectional area was represented by a sector with width b_i , depth h_i and angle $\beta = 2\arctg(b_i/2h_i)$ under the segment (see view A–A in Fig. 1, *a*). Then, according to Ref. [18],

$$F_{\text{def.long},i} = \frac{r_i^2(\beta_i - \sin \beta_i)}{2}, \quad (22)$$

where $r_i = (h_i^2 + b_i^2/4)^{1/2}$, which after transformations gave:

$$F_{\text{long,seg},i} = \frac{1}{2}(h_i^2 + \frac{b_i^2}{4})(\beta_i - \sin \beta_i),$$

and according to (7) and taking into account $d_{1i} = 2r_i$, we obtained:

$$K_{\text{CID,long}} = \frac{1}{1 - (2h_i^2/(\pi d_{1i}^2) + b_i^2/(2\pi d_{1i}^2))(\beta_i - \sin \beta_i)}, \quad (23)$$

Similarly, for the defect transverse orientation on the wire, its cross-sectional view, which is perpendicular to the drawing axis, taking into account the notches method of applying to the workpiece, was approximately represented by a segment (see view B–B in Fig. 1, *b*). The area of this figure is determined by the formula (18) [18]:

$$F_{\text{def.tran},i} = \frac{r_i^2(\beta_i - \sin \beta_i)}{2}, \quad \beta_i = 2 \arccos((d_{1i} - 2h_i)/d_{1i}),$$

and, after simple transformations, we obtained:

$$K_{\text{CID,tran}} = \frac{1}{1 - (\beta_i - \sin \beta_i)/(2\pi)}, \quad (24)$$

Calculation according to formulas (23) and (24) showed that the impact K_{def} on the stability of the drawing process is most significant in the first passes, which requires, according to equation (4), an increase in the limiting safety factor according to formula (1) and a corresponding decrease by 5–30% of the drawing elongation μ_i .

Evaluation of the information presented above determined the feasibility of conducting additional investigations to identify deformation patterns in comparable conditions of surface defects with the same initial orientation of the axes relative to the rod axis and their influence on the condition (4) of continuous drawing. Also, the formula for estimating the coefficient K_{def} was subject to appropriate definition. This became the aim of the following experiments and analysis.

3. RESEARCH SECTION

To achieve the set purpose, we used 5 samples of wire rod, prepared in the same way for drawing according to the method presented in Ref. [11] and shown above.

On each wire rod sample made of low-carbon steel, groups of conical non-through holes (Fig. 3, *a*) with a depth $h_0 = 3.0$ mm and dimensions $b_0 = a_0 = 6.0$ mm; $h_0 = 2.0$ mm and $b_0 = a_0 = 4.0$ mm; $h_0 = 1.0$ mm and $b_0 = a_0 = 2.0$ mm were applied with a drill with an angle at the apex of 90°. Such models conditionally reflected defects: scale detachment, non-metallic surface inclusions, small shells, *etc.*, better than those ones oriented only along the axis or perpendicular to the drawing axis.

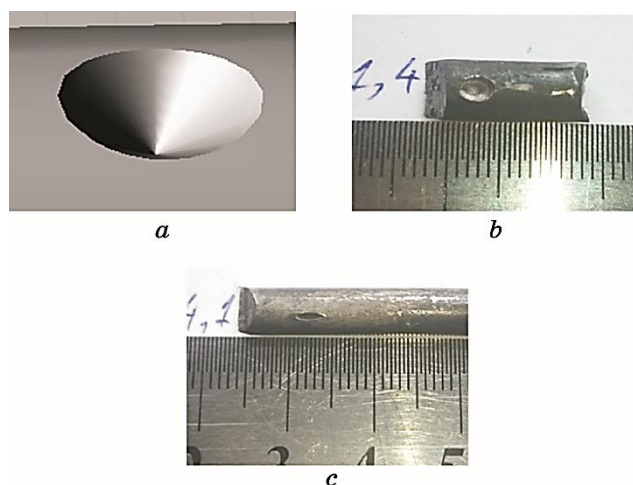


Fig. 3. General view: conical model of the surface ‘defect’ (magnification $\times 10$) (*a*), wire fragment after the first pass with a deformed defect (magnification $\times 2$) (*b*), the same after the fourth pass (*c*).

Prepared samples of wire rod with applied conical ‘models’ of surface defects were deformed on a chain drawing mill under the conditions presented above.

Then, after each i -th pass, a section with the next deformed ‘defect’ was cut from the rear end of the sample with a diameter d_{1i} (Fig. 3, *b*, *c*). Then, each of them was cut perpendicular to the axes of the wire and the ‘defect’ into templates, polished, photographed with a known magnification using a digital camera and transferred to the PC screen. The characteristic dimensions of the ‘defects’ were measured with an instrumental ruler of the second accuracy class with a division value of 0.5 mm and the results of similar measurements were averaged.

The negative impact of image boundaries blurring with increasing computer magnification on measurement accuracy was taken into account using the conversion factor K_κ , which was determined by the relationship:

$$K_\kappa = 10/N, \quad (25)$$

where N is the number of pixels per 10 mm of the template (photographed together with the samples).

This approach allowed us to reduce the relative error in measurements of the geometric parameters of ‘defects’ and the wire to 2%. Strictly speaking, the results obtained in such discrete investigations should be presented as bar charts. However, for the convenience of comparing the newly obtained data with similar ones, they were presented as lines on graphs that displayed the trends in the change of characteristic indicators during the deformation of surface defects depending on the values of the total drawing elongation $\mu_\Sigma = (d_0/d_i)^2$ in a similar way as in Ref. [11].

The analysis determined the next. Absolute values of depth h_i and width b_i (taking into account that the initial round base of the cylindrical ‘defect’ on the wire surface after the first drawing pass transformed into an elliptical figure with a width b_i and length a_i that changed in successive i -th drawing passes of the wire rod and wire (Fig. 4). The ratio h_{i-1}/h_i , which reflected the intensity of the decrease in the depth of the ‘defect’ with an increase in μ_Σ , the ratio b_i/h_i , which was consistent with the change in the angle β_i and reflected the tendency to smooth out or transform the conical ‘defect’ into a crack; the ratio $K_{2i} = b_i d_{i-1}/(b_{i-1} d_i)$ also assessed the synchronicity of the change in the width of the ‘defect’ with the perimeter (diameter) of the wire (Fig. 5).

4. DISCUSSION OF RESULTS

Analysis of the presented data indicated the following. In the presence of conical models of ‘defects’ on the wire rod with a change in the total

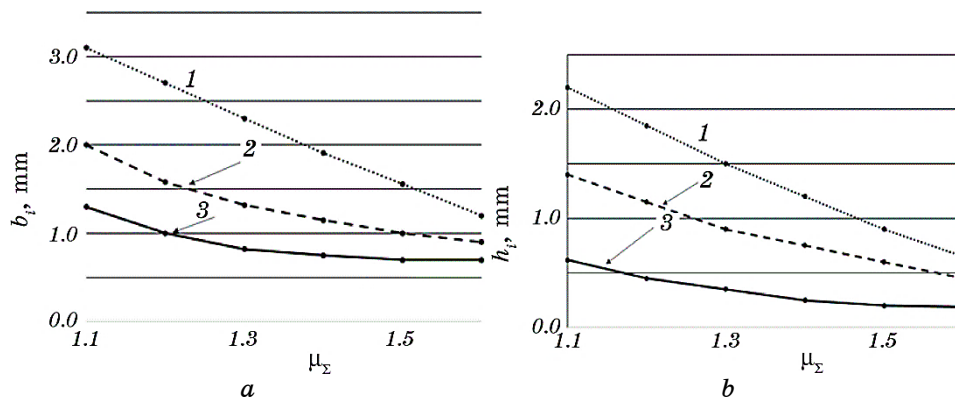


Fig. 4. Dependence of the total extraction depth (a) and width (b) of conical models of 'defects': 1— $h_0 = 3.0$ mm and $b_0 = a_0 = 6.0$ mm, 2— $h_0 = 2.0$ mm and $b_0 = a_0 = 4.0$ mm, 3— $h_0 = 1.0$ mm and $b_0 = a_0 = 2.0$ mm.

draw over several passes during drawing, the width b_i and depth h_i of the defect on the wire monotonically decreased the more intensively the larger these initial parameters on the wire rod were.

Qualitatively, this was consistent with the corresponding data of work [11] and the results of calculations using formulas (8)–(17). At the same time, a noticeable manifestation of the volumetric scheme of deformations and stresses was detected, as a result of which the quantitative data differed. In particular, the intensity of the change $h_{i-1}/h_i > 1$ and $b_i/h_i > 1$ indicated a positive trend in the smoothing of defects, the greater the larger μ_Σ was (see Fig. 4). To a greater extent, this was consistent with the 'behaviour' of transverse defects (see Ref. [11]). The values $K_{2i} = b_i d_{i-1} / (b_{i-1} d_i) \cong 1$ indicated an approximate synchrony of the change in the width of the 'defect' and the perimeter (diameter) of the wire (see Fig. 5), which was the largest at larger values h_0 , b_0 and decreased with a decrease in these parameters from μ_Σ indicates the influence of a predominantly volumetric scheme of metal deformation around the conical defect, in contrast to predominantly linear schemes with its longitudinal or transverse orientation relative to the drawing axis.

In further analysis, the influence of surface conical defects of the workpiece on the stability of the process of its multiple drawing by changing the geometric parameters in the drawing process, similar to previous investigations [11], was estimated by the value of the defect coefficient according to formula (7). It was taken into account that the geometric 'weakening' of the wire profile at the exit from the drawing was due to the corresponding sizes b_i , h_i and d_{1i} in the cross-section of the 'defect' and the wire.

In Figure 6, *a*, the cross-section of the conical defect model is repre-

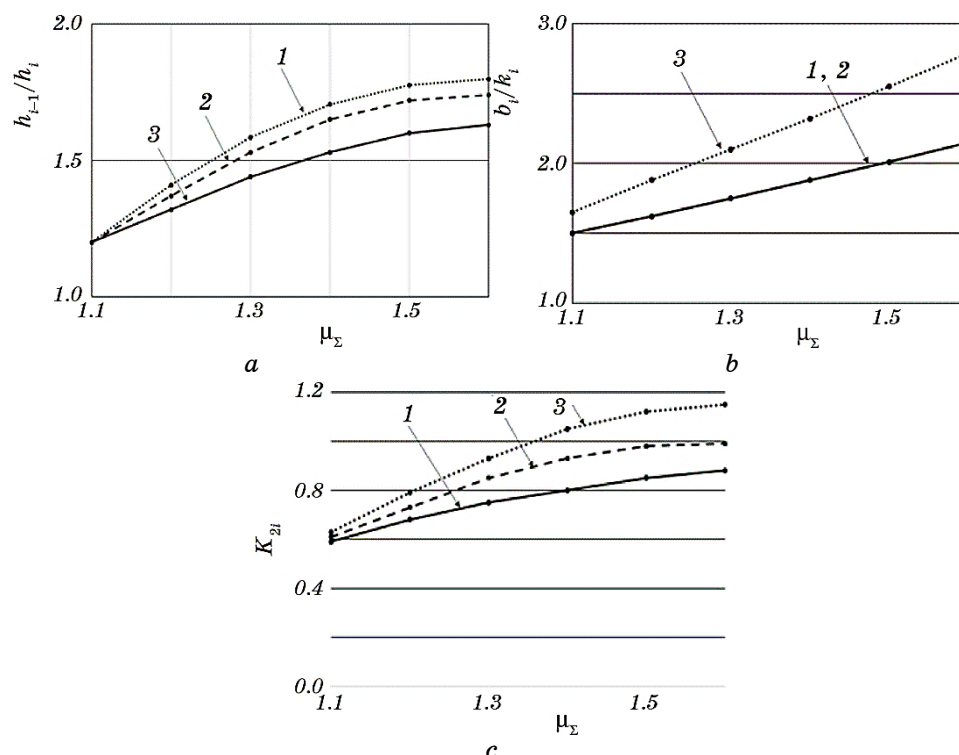


Fig. 5. Dependence of the intensity of the change in depth (a), relative width (b) and synchronicity of the change in the width of the 'defect' with the perimeter (diameter) of the wire (c) on the total draw for conical models of 'defects': 1— $h_0 = 3.0$ mm and $b_0 = a_0 = 6.0$ mm, 2— $h_0 = 2.0$ mm and $b_0 = a_0 = 4.0$ mm, 3— $h_0 = 1.0$ mm and $b_0 = a_0 = 2.0$ mm.

sented by a curvilinear triangle AKBC with width b_i , depth h_i and angle β_i under the corresponding arc AKB, on which the central angle α_i of the circle corresponding to the cross-section of the wire also rests. The area of the 'defect' consists of the sector AKB of the circle with diameter d_{1i} and the triangle ABC: $F_{\text{def.i.con}} = F_{\text{AKB}} + F_{\text{ABC}}$.

With this representation according to Ref. [18],

$$F_{\text{AKB}} = \frac{r_i^2 (\alpha_i - \sin \alpha_i)}{2},$$

where $r_i = d_{1i}/2$, angle $\alpha_i = 2\arcsin(b_i/d_{1i})$ in radians, $F_{\text{ABC}} = 0.5h_i b_i$, and after simple transformations taking into account (7) we obtained:

$$K_{\text{CID.con}} = \frac{\pi d_{1i}^2}{\pi d_{1i}^2 - 0.5 d_{1i}^2 (\alpha - \sin \alpha) - 2 h_i b_i}. \quad (26)$$

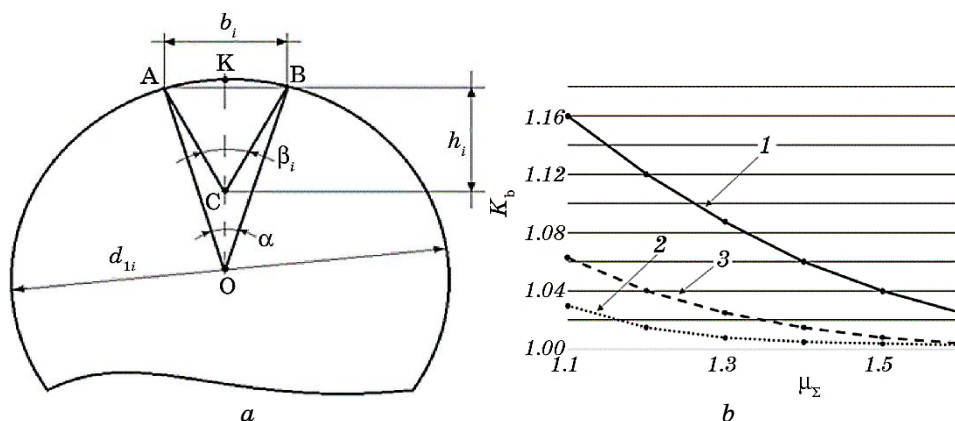


Fig. 6. Scheme for determining the area of the conical defect model in the cross-section of the wire at the exit from the drawing (*a*) and the dependence of the defect coefficient on the metal extraction during drawing (*b*): 1— $h_0 = 3.0$ mm and $b_0 = a_0 = 6.0$ mm, 2— $h_0 = 2.0$ mm and $b_0 = a_0 = 4.0$ mm, 3— $h_0 = 1.0$ mm and $b_0 = a_0 = 2.0$ mm.

Next, using the experimental values of b_i , h_i and d_{1i} (see Fig. 4), we determined the dependence of the parameter $K_{\text{CID.con}}$ on μ_Σ (Fig. 6, *b*).

The obtained data showed that, in agreement with the tendency to smooth out conical defects (see Figs. 4 and 5), their negative impact on the stability of the drawing process decreased with decreasing wire diameter, the deeper the initial ‘defect’ was. At the same time, the absolute values $K_{\text{CID.con}}$ were the smallest at small values h_0 . This, to some extent, is consistent with the data presented in Ref. [11] and calculations using formulas (18) and (19). The quantitative difference can be explained by the significant influence of the stress–strain state of the metal around the defect on its formation, while maintaining the recommendation regarding the need to weaken the deformation regime, *i.e.*, the values of μ_i , along the entire drawing route, the greater the depth of the defect and the value of μ_Σ , which is consistent with production practice.

The results of the research also showed that drawing of wire with surface conical defect models is accompanied by an increase in their longitudinal dimensions relative to the wire axis. At the same time, a difference was recorded between the relative elongation of the linear dimensions of defects closer to the axis and on the wire surface: on the surface, they were larger by 15–40%. The latter indicated the uneven deformation in the drawing of both the wire and the defects on it.

It should be noted that the presence of cone-shaped defects on the wire surface, as well as defects with a transverse location relative to the drawing axis, forms a stress concentrator for the acting longitudi-

nal drawing force. This can affect additionally negatively the stability of continuous drawing, which requires an even greater reduction in the deformations μ_i in the gaps and changes the right-hand side of inequality (4):

$$\gamma = \frac{\sigma_{B1}}{\sigma} \geq K_{\sigma} K_{\text{def}}[\gamma], \quad (27)$$

where $1 < K_{\sigma} < 3$ is the technical stress concentration coefficient for the conditions of plastic deformation of the material [19].

It can be argued that the preferred longitudinal orientation of the defect relative to the tensile force vector during drawing is less sensitive to stress concentration.

The obtained data may be useful in developing models of a stable (continuous) wire rod and wire drawing process.

5. CONCLUSIONS

Using the developed method, the deformation regularities of artificial models of cone-shaped defects on wire rod and wire during frequentative drawing were experimentally determined for the first time. It was found that, in most cases, the smoothing of such defects occurs more intensively, the greater the total wire drawing and the initial values of the depth and width of the defects.

The influence of defects on the condition of stable (unbroken) wire drawing is determined. The data are compared with the results of previous similar investigations on wire deformation in the presence of defects of predominantly transverse and predominantly longitudinal orientation relative to the drawing axis. It is shown that the qualitatively obtained new results are closer to the regularities of deformation of ‘transverse’ defects, and the quantitative differences can be explained by the presence of a volumetric scheme of the stress–strain state of the metal around the defect.

Attention is drawn to the probable additional influence of conical and ‘transverse’ defects as stress concentrators on the condition of continuous drawing, which is also advisable to take into account when designing routes for multiple deformation of the workpiece to obtain drawn wire of acceptable quality. A promising direction of research is to combine the data of existing work with known methods for calculating force conditions of deformation and thorough design of routes for multiple stable wire drawing.

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