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# Prediction of Changes in the Mechanical Properties of the Metal at Cold Pilger Rolling

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The article contains experimentally obtained dependencies that by common usage permit to predict the mechanical properties of the metal as after a cycle of cold pilger rolling, and along the length of the deformation zone. These dependencies link specific strain parameters to found criterion of changes in mechanical properties. The final dependences and technique for predicting of changes of the properties were experimentally verified.

Keywords: COLD PILGER ROLLING, MECHANICAL PROPERTIES, YIELD STRENGTH, TENSILE STRENGTH

## Introduction

Segment of the tube market for different branches of engineering is the most stable today for seamless steel tubes, what are produced by cold pilger rolling. At the same time, engineering makes strict demands on quality of tubes. These demands include:

- the use of complex alloyed austenitic, ferritic, martensitic, polyphase and in the future TRIP and TWIP steels that have high consumer properties;
- the minimum deviation of the actual geometric dimensions of tubes from the nomina;
- the predictable level of metal properties.

The predictable level of properties of metal of finished tubes takes a special place in this list, in particular the ultimate and yield strength, which in accordance with the requirements of most standards and specifications, determine the capability of the tubes for further deformation processing as with intermediate heat treatment and without it. Thus, the prediction of the properties of the metal of tubes is necessary to determine the resource of the metal properties in the calculation of deformation modes at cold pilger rolling, as well as for determining the properties of finished tubes.

Many researches cover receiving tubes with high level of quality in the geometric dimensions, at the same time as the management of the properties of the metal of cold-deformed tubes has not yet been sufficiently developed [1, 2]. This leads to a significant increase in the number of production operations and increased consumption of metal and resources.

Meeting the demands, that are put forward to the cold-rolled tubes, requires a complex review of methods of calculation the deformation modes, which had been established in other, less strict demands on product quality and production efficiency. According to the known methods of calculation of the deformation modes, at cold pilger rolling deformation of diameter and wall thickness has a cumulative effect on a change in the properties of the metal [3]. This approach was adequate when the main factors, that limited the intensification of production, were the rolling force and the stableness of the equipment [4]. Prediction of properties of a tube after rolling with sufficient accuracy in this case was impossible. With the development of requirements to quality of tubes and deformation capability of the process, separate study of the influence of diameter and thickness reduction on change of the metal properties, as parameters, which provide a change in sign of the stresses in the deformation zone [5].

The result of this study should be a deformation mode, which will provide the necessary distribution of partial strain partial strain in diameter along the length of the working cone for each case of rolling with the changing characteristics of the material parameters of the rolling mill and other processing elements [6, 7].

Cross-sectional shape plays an important role through regulating the flow of metal in a tangential direction and also provides alternating of deformation at the turn of the cone, which in turn also influences on the change in the properties of the metal [8, 9]. However, the level of research in this area can not reasonably coordinate the development of deformation in the longitudinal and transverse directions with the influence of the deformation distribution in the diameter and wall thickness on the change of the metal properties. This results in damage of tube surface, intense hardening of the metal, and, in turn, increases the number of technological operations at the production of precision tubes.

Change in the metal properties at cold pilger rolling is influenced by both deformation and thermal factors. The final temperature, the properties for the prior cross-section of the working cone become initial for the next one. During the stroke of the working stand, this process is continuous.

The ratio of the ultimate strength $\sigma_в$ and the yield strength $\sigma_т$ (**Figure 1**), that was obtained at tests on the tensile-testing machines, enables to determine the resource of the metal properties $k_\sigma$ and the coefficient of its use $S_\sigma$ at cold pilger rolling according to the following dependences [10]:

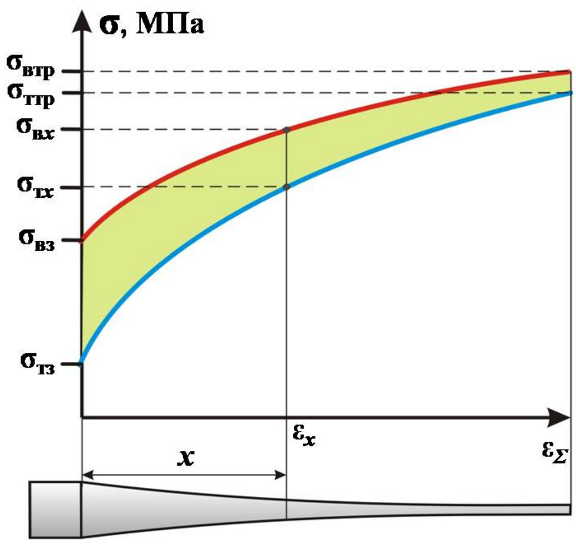


**Figure 1.** Scheme to the determination of the index of the changes in the mechanical properties $k_\sigma$

- for tube-billet: $k_{\sigma з} = \dfrac{\sigma_{вз}}{\sigma_{тз}}$, where $\sigma_{вз}$ – the ultimate strength of the metal of the tube before rolling; $\sigma_{тз}$ – the yield strength of the metal of the tube before rolling;

- for finished tube at the coming out of the mill, rolled with the total deformation $\varepsilon_\Sigma$ (before heat treatment) $k_{\sigma тр} = \dfrac{\sigma_{втр}}{\sigma_{ттр}}$, where $\sigma_{втр}$ – the ultimate strength of the tube after rolling; $\sigma_{ттр}$ – the yield strength of the tube after rolling;

- for the control cross-section x of the working cone, which was preceded by deformation $\varepsilon_x$: $k_{\sigma x} = \dfrac{\sigma_{вх}}{\sigma_{тх}}$, where $\sigma_{вх}$ – the ultimate strength of the specimen that was cut out from the working cone; $\sigma_{ттр}$ – the yield strength of the specimen that was cut out from the working cone;

- for the evaluation of use of the resource of the metal properties in the area of the total deformation (working *cone):* $S_{\sigma\Sigma} = \dfrac{k_{\sigma з}}{k_{\sigma тр}}$, for evaluaion the use of the resource of the metal properties in the deformation zone that is prior to the cross section *x:* $S_{\sigma\Sigma} = \dfrac{k_{\sigma з}}{k_{\sigma x}}$. For determination $\sigma_{вx}$ and $\sigma_{тx}$ specimens were cut out so that the middle of its working part coincide with the control cross-section, separated from the beginning of the working cone at a distance *x*.

The lower boundary of possible values of $k_\sigma$ tends to unity, which corresponds to the equality $\sigma_в$ and $\sigma_т$. Under these conditions, the possibility of micro- and macro- destruction is the greatest. The upper limit determined by the properties of the metal. In practice, among the materials, of which cold-deformed tubes in the state after the heat treatment are made, a maximum value reaches 3, 4 (copper).

Steels, used at the manufacturing of precision tubes, are characterized by such values of $k_{\sigma з}$: ferritic – 1.2...1.6; martensite – 1.4...1.7; austenitic – 1.9...2.4; two-phase – 1.5...1,8; TRIP – 2,1...2,2; TWIP – 2,2...2,5.

According to the results of experimental researches [10], next had been determined, that the resource of metal properties decreases after rolling in all cases. For tube-billets range of values $k_{\sigma з}$ is in the range 1.56...2.4 and for the finished tubes (without treatment) – 1.01...1.5. The value of the use of the resource of the metal properties $S_\sigma$ for all methods of tool calculation and methods of rolling in the range 1.44...1.98.Analysis of the results had shown that the higher the value of $S_\sigma$ – the more intensively the resource of the metal properties is used, that negatively characterizes the deformation process and increases the probability of occurrence of microdestruction in the metal.

Analysis of deformation parameters at cold pilger rolling, in terms of their influence on change in the metal properties, had shown that at increasing of the part of the diameter deformation in the total deformation $\varepsilon_D/\varepsilon_\Sigma$ of the rolling schedule leads to a stable, with varying degrees of intensity, increase of the values $S_\sigma$ for all cases of rolling.

Definition of the boundary conditions for the dependence $S_{\sigma\Sigma} = f(\dfrac{\varepsilon_D}{\varepsilon_\Sigma})$ had shown that at

$\left(\frac{\varepsilon_D}{\varepsilon_\Sigma}\right)=0$ the process of pilger rolling becomes impossible from a kinematic point of view, respectively, the resource of the properties of the finished tubes is equal to the resource of the properties of the tube-billet. The deformation of the wall thickness at $\left(\frac{\varepsilon_D}{\varepsilon_\Sigma}\right)=1$ is nonpresent, which determines the maximum values of $S_\sigma$. This correlates with the known data about the negative impact of the reducing on properties of the metal of the tubes [11-13].

Change of the coefficient of use of the metal properties in dependence from the fraction of the total deformation of diameter with sufficient accuracy can be described by the relation:

$$S_{\sigma\Sigma}=e^{b_D\left(\frac{\varepsilon_D}{\varepsilon_\Sigma}\right)}, \qquad \text{(Eq. 1)}$$

where $b_D$ – a intensity coefficient of using of the metal properties.

This coefficient can be considered as a criteria for estimation the effectiveness of technological elements of cold and warm pilger rolling in terms of usage of the resource of the metal properties. It allows to compare the methods of calculation tools and methods of rolling with the terms of the effect of thermal, kinematic and deformation parameters of the process to change the properties of the metal in the process of cold pilger rolling. The coefficient in the range from 0, which corresponds to the conditions of the "ideal" process (the properties of the metal does not change) to 1, which is a sign of "irrational process" (resource properties used with the maximum intensity). The main influence on the intensity of use of the resource properties have parameters such as the shape of the tool, the deformation and thermal modes of rolling.

The relation of these parameters can be expressed by the empirical relationship that was obtained at the experimental studies, conducted on the one stand mills for tubes of stainless steel:

$$b_D=\frac{m}{k_b n_\sigma}\mu_\Sigma^{(1-k_{\sigma з})}, \qquad \text{(Eq. 2)}$$

where m – feed; $\mu_\Sigma$ – total reduction ratio; $k_b$ – coefficient that takes into account cross-sectional shape of the working cone; $n_\sigma$ – deformation fractional index, which depends on the length of the total deformation zones, which in turn is specified by the shape of the tool; $k_{\sigma з}$ – the resource of the properties of tube-billet, that in this case, takes into account changes in the properties from the effect of warm deformation.

Subject to the increase of the deformation on the length of the working cone, dependence (1) can be written in the form of a constraint equation of the deformation mode and changes in the properties of the metal:

$$\frac{\varepsilon_{Dx}}{\varepsilon_x}=\frac{lnS_{\sigma x}}{b_D}, \qquad \text{(Eq. 3)}$$

where $\varepsilon_{Dx}$ – total partial strain of the diameter; $\varepsilon_x$ – total partial strain of the area of the cross section; $S_{\sigma x}$ – coefficient of use of the resource of the metal properties in the cross section x. Intensity factor of using the properties $b_D$ in this case should be determined by the dependence (2) for the rolling schedule in whole.

In equation (3) the deformation parameters $\varepsilon_{Dx}$ and $\varepsilon_x$ are defined according to the dimensions of the tube-billet.

In the calculations of the deformation modes for cold pilger rolling, method of proportionality of partial strain is realized by introducing in a formulas for tool calculation the intensity index of the distribution of the partial strain n. Measure this are dealt with in [14, 15]. Equality of this index for calculation the form of the stream gauge and mandrel provides a constant ratio of the partial strain of the diameter and wall thickness throughout the working cone.

For this is possible to use the function of change in cross-sectional area of the working cone, which takes into account the index of the distribution intensity of partial strain n:

$$F_x=\frac{F_з}{\mu_\Sigma^{\left(\frac{x}{l}\right)^n}}, \qquad \text{(Eq. 4)}$$

where $F_x$ – cross-sectional area at a distance x from the beginning of the working cone; $F_3$ – cross-sectional area of the-billet; l – length of the working cone; $\mu_\Sigma$ – total reduction ratio.

Experimental tests of changes in the properties of the metal at cold pilger rolling [16] showed that the change in the yield stress can be written as a dependence on the deformation of cross-sectional area and the change in the tensile strength – as the dependence on the diameter deformation:

$$\sigma_{mx}=\sigma_{mз}+a\varepsilon_x^m, \qquad \text{(Eq. 5)}$$

$$\sigma_{вx}=\sigma_{вз}+b\varepsilon_{Dx}^q. \qquad \text{(Eq. 6)}$$

For the determination of the deformation fraction in the diameter in deformation $\varepsilon_{Dx}$ in the cross-section area $\varepsilon_x$ shall be imposed additional conditions:

1) $S_{\sigma x}\le S_{\sigma\Sigma}$ ((determined by the rolling schedule);

2) fraction of the diameter deformation in the total deformation $\varepsilon_{Dx}/\varepsilon_x$ for the rolling schedule is in the range 0.25 ... 0.75, which corresponds to the majority of schedules of cold and warm pilger rolling;

3) values of coefficients in relation (5) and (6) meet such conditions: a> b; 1> q> m.

According to the mentioned above conditions, the relationship of the diameter deformation and deformation of the cross sectional area along the length of the working cone can be written as:

for $\varepsilon_D/\varepsilon_\Sigma = 0{,}25\ldots0{,}6$:

$$\varepsilon_{Dx} = \left[\frac{\sigma_{m з}}{\sigma_{в з}}\varepsilon_x\left(1-\frac{b}{a}\right)\right]^{\left(\frac{q}{m}-1\right)^{\frac{1}{k_b}}} \qquad \text{(Eq. 7)}$$

for $\varepsilon_D/\varepsilon_\Sigma = 0{,}25\ldots0{,}6$:

$$\varepsilon_{Dx} = \left[\frac{\sigma_{m з}}{\sigma_{в з}}\varepsilon_x\left(\frac{b}{a}\right)\right]^{\left(\frac{q}{m}-1\right)^{\frac{1}{k_b}}} \qquad \text{(Eq. 8)}$$

where a, m – coefficients depending on the (5); b, q – coefficients depending on (6).

Calculation of fraction distribution of deformation in the diameter in the deformation of the cross-section area (fig. 3) had shown that the method of constant partial strain (1, **Figure 2**) [4] is characterized by two-zone change in the share of deformation along diameter: a sharp drop in the zone of free reducing to the contact of the inner surface of the working cone with the mandrel and a gradual increase in the area of joint deformation of the diameter and wall thickness. The method of proportional partial strain (2, **Figure 2**) [1] is characterized by a constant fraction of the diameter deformation along the entire length of the working cone. Distribution of the partial strain ses along the diameter, which is based on equations (3), (7), (8) connections of the deformation parameters and change in the properties (3, **Figure 2**) [10], provides a decrease in the proportion of deformation in the diameter in accordance with changes in the properties of the metal.

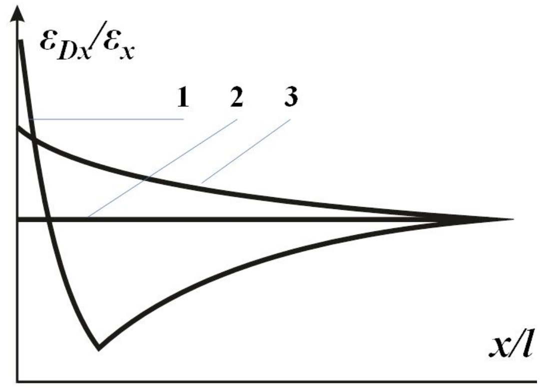


**Figure 2.** The scheme of distribution of the deformation fraction in the diameter in the total deformation along the length of the working cone for different methods of distribution of deformations: 1 – the method of constant partial strain, 2 – a method of proportional reductions, 3 method that is based on equations (3), (7), (8)

These equations allow to predict and adjust the properties of the tubes after rolling. At the rolling of tubes 304 (AISI) according to the rolling schedule 38x3,6 → 18x1,5 mm was found that the difference between the predicted and actual properties were follows: 5.7%, with greater values for both $\sigma_в$, and $\sigma_т$.

The method of equivalent cross-sectional dimensions of the working cone at cold pilger rolling is aimed at developing a method of a frame tool construction [17], which define the size of the cross-section of the working cone not in coordinates $B_x$ and $D_x$, what is a tradition for cold pilger rolling, and with the coefficient $k_b$,which characterizes the deviation of the actual cross-sectional dimensions, in particular $D_{0x}$ of equivalent dimensions, in particular $D_{екв}$ according the polar angle φ (**Figure 3**).

Effect of cross-sectional shape of the working cone on the change in the properties of the metal is taken into account by equation (10), which can be found in the following form:

$$\frac{(D_{x-1}k_{bx-1} - D_x k_{bx})/D_{x-1}k_{x-1}}{1-1/((D_{x-1}k_{bx-1}-t_{x-1})t_{x-1}/(D_x k_{bx}-t_x)t_x} = \frac{\ln(\sigma_{вx-1}\sigma_{mx}/\sigma_{вx}\sigma_{mx-1}}{b_x}, \qquad \text{(Eq. 9)}$$

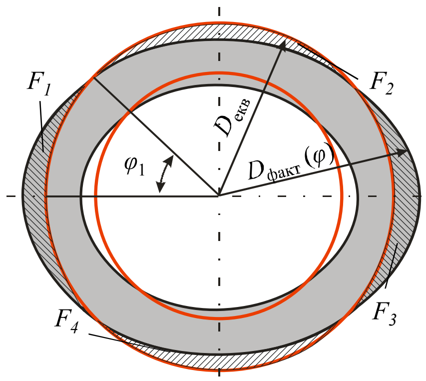


**Figure 3.** Scheme to the determination of the equivalent cross-sectional dimensions

which implies that changing the value $k_b$ from the cross section (x-1) to the cross section (x) of the working cone, it is possible to effect on the distribution of the portion in the diameter in deformation of the area of the cross section and, correspondingly, on the intensity of use of the resource of the metal properties:

$$\frac{D_{еквx-1} / D_{x-1}}{D_{еквx} / D_x} \rightarrow k_{bx-1} - k_{bx} \rightarrow \frac{\varepsilon_{Dx}}{\varepsilon_x} \rightarrow \frac{lnS_{\sigma x}}{b_D} \quad \text{(Eq. 10)}$$

At the experimental rolling of tubes 316 (AISI) according to the reduction scheme 48×3,9→25,4×2,11 mm using a tool, which $k_{bx}$ is varied along the length of the working cone from 0.32 to 0 (option 1) and by using the tool, the ratio of $B_x/D_x$ was varied along the length of the working cone from 1.09 to 1 (option 2) has been established that the resource of the metal properties $k_\sigma$ and the coefficient of the properties resource using $S_\sigma$ in rolled tubes were: for option 1 – $k_\sigma$ = 1,46; $S_{\sigma x}$ = 1,37; for option 2 – $k_\sigma$ = 1,35; $S_{\sigma x}$ = 1,47.

The results of mathematical modeling of cold pilger rolling of tube with variable shape of the cross-section [18] showed that the lowest level of deformation unevenness is characterized to calibers, which $\cos\varphi_1$ has low values, for example the calibers with release on a tangent. However, significant levels of stress arising in the metal, resulting in excessive loads on the parts of the stand. In addition, the increase of $\cos\varphi_1$, which is characteristic, for example, to oval caliber, along with a decrease in stress leads to an increase in tensile stresses in the zone of the taper of groove. This, in turn, negatively effects on the mechanical properties of the metal at the deformation process.

In general, the source data for prediction the properties of the metal of the rolled tubes are: the properties of the-billet ($\sigma_{вз}$ and $\sigma_{тз}$), the deformation parameters ($\varepsilon_D$ and $\varepsilon_\Sigma$),as well as the intensity factor of the use of the metal properties $b_D$. The value of this coefficient is determined depending on (2), or experimentally for groups of reduction schemes, which are characterized by a certain set of technological elements: the method of calculating the deformation mode, thermal mode of rolling, the magnitude of feeding, the length of the working cone, the type of mill, the total deformation per pass, the characteristic changes in cross-section of the working cone $k_b$. Further, depending on (1) the relation of the properties of the metal $S_{\sigma\Sigma}$, corresponding to the reduction schema in given conditions of technological elements.

To obtain the estimated (predicted) value of the resource of the metal properties $k_{\sigma тр}$ of the tube, which is rolled at the given parameters of the deformation, the resource of metal properties of-billet $k_{\sigma з}$ has to be divided into the resulting factor for the properties of the metal $S_{\sigma\Sigma}$, corresponding to this reduction scheme.

Transition to the absolute values of strength and yield stresses of the metal of tube after rolling is carried out by the dependences (5) and (6).

At the experimental test was revealed that the maximum error in predicting of the resource of the properties is 8.37%. The increase in the resource of the metal properties through the use of the developed technological mode that is based on predicting the properties of the metal [19] for all routes is 6.22...14.04%.

**Conclusions**

An increase in the deformation fraction in the diameter of the total strain for all the researched schedules and technological elements of cold pilger rolling leads to reducing of the ratio of the ultimate strength to the yield strength, defined in the article as the resource of the metal properties. The intensity of this reduction depends on the deformation parameters and the technological elements of the process, in particular on the method of mode deformation calculation, the thermal mode of rolling, equipment parameters and the feed volume. It was determined that the ratio of the resource of the metal properties before and after deformation is an index of using the metal properties in the particular conditions of deformation. The index, which can range from 0 to 1 to evaluate the effectiveness of technological elements in terms of resource usage of the metal properties, had been received and verified. The method for determination of the equivalent cross-sectional dimensions of the working cone, taking into account the cross-sectional shape of the working cone along the length of the perimeter of the die, had been developed. The recommendations on the level of prediction of the metal properties in industrial conditions and methods of predicting the metal properties after cold pilger rolling had been developed. The level of error in predicting the properties of the tubes after rolling had reached 0.24...8.37% at investigation of industrial rolling schedules.

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## Прогнозирование изменения механических свойства металла в условиях холодной пильгерной прокатки

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В статье приведен ряд полученных экспериментально зависимостей, которые при совместном использовании позволяют прогнозировать изменение механических свойств металла как после цикла холодной пильгерной прокатки, так и по длине зоны деформации. Эти зависимости связывают определенные параметры деформации с показателем изменения механических свойств. Полученные зависимости и методика прогнозирования изменения свойств проверены экспериментально.