Study of localized plastic strain taking into account the stages of plastic flow

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Abstract. The article presents the results of a study of the localization of plastic flow in high-temperature tensile rod samples of alloy 12Cr18Ni10Ti. Research is aimed at increasing the efficiency of thermal force treatment to ensure geometrical accuracy and stability of the material properties of the workpieces. The uniformity of deformation along the axis of the samples in the marked zones was studied. The localization degree was estimated by the localization parameters of two types. The features of this localization, which are directly related to the stages of plastic flow, were revealed. These stages are determined from the experimental stress-strain curve. The results of statistical processing of the elongations uniformity of the marked zones are given taking into account the stages of the plastic flow corresponding to the operating temperature. The maximum degree of uniformity of deformation along the length is provided if the deformation reaches the stage of parabolic hardening on the curve of plastic flow.

1. Introduction
The material consumption of machine designs is constantly reduced due to the development of engineering techniques, improvement of physical-mechanical properties of materials. At the same time the dimensional accuracy become tougher and the performance criteria are increased. For these reasons, technological difficulties are growing in the manufacture of these products.

A special class of low-rigid parts includes axial-symmetric long-length parts such as a shaft or a tube. The processes of spontaneous relaxation of residual stresses lead to warping in the in-process period, increasing the total manufacturing time. In the operational phase, this reduces the operational performances of machines and leads to their failure due to breakdowns.

To solve these problems, a systematic approach is required in the design of technological processes for the manufacture of non-rigid parts, taking into account the principles of technological inheritance. The main stage of manufacturing technologies is the blanking operation.

It forms both the geometrical shape of the part and the set of physical-mechanical properties of the material with its structure.

Special barriers to the properties of the work-piece material and its structure transfer from the beginning of the technological process to its completion are thermal operations [1].

To form a uniform stress-strained state of the material, a thermal force treatment of axial-symmetric parts has been developed, which also contributes to the formation of the straightness of the workpieces [2].
2. Actuality
The relevance of providing a set of geometric and physical-mechanical properties at the highest level is determined by the widest range of products from the category of non-rigid parts for important purposes. The application range of parts with a ratio of length to diameter more than 10 is very diverse for which it is necessary to use of thermal force treatment. This technology can be used for parts with wide sizes range from small axial tools (drills, core drills, boring bars) to large rotor shafts, pipes, submersible pumps, cylinders and rods of pneumatic and hydraulic systems, etc.

The principal of thermal force treatment is the simultaneous heating of the workpiece to the working temperature according to the heat treatment technology (normalization, tempering, quenching) with the application of power loads. These loads can be axial, compression or tension, as well as shearing ones. Force loading can be complex (for example, in the manufacture of torsion bars). Owing to the material heating, the yield strength is reduced, and less effort is required to exceed the yield point.

The main technological parameters of the thermal force treatment mode are heating temperature, strain and strain rate. Straightness is provided with the correct choice of the elongation of the work-piece, taking into account the initial curvature of it. The problem, to which our study aims, is to align the deformation zones of the work-piece along its length. When the deformation is localized along the length of the workpiece, the thinning in different areas comes unevenly. This worsens the processing conditions, since the longitudinal profile with an error is formed on the length of the work-piece. This also affects the stability of the axial dimensions. For example, in the manufacture of screws it will be expressed in the instability of the thread pitch. The task is to determine the area of thermal force treatment mode, which provides maximum uniformity of deformation of the workpiece along the length, taking into account the peculiarities of deformation processing.

The strain – stress dependence is essentially nonlinear and consists of characteristic stages: linear for elastic deformation, yield plateau, followed by stages of linear hardening, then parabolic hardening and prefailure stage. The following stages are allocated on stress-strain curve: first stage is a yield plateau or a stage of easy sliding, which corresponds to a solitary zones of local deformation; second stage is linear hardening stage, on which several equidistant localized deformation zones are moved; third stage is a part of curve with parabolic hardening, on which the stationary equidistant localized deformation zones formation takes place.

Studies of strain localization under tension have been considered previously. The main results in the study of localized plastic strain based on the principles of mesomechanics and synergetic [3, 4] are as follows. The localization of strains along the length of the sample is determined by autowave processes of plastic deformation. The peculiar properties of plastic strain or patterns of localized plasticity, are determined by the stage of plastic flow, which is achieved under loading. The stages correspond to a discrete change in the parabolic index n in the equation approximating the plastic flow curve

$$\sigma(\varepsilon) = \sigma_0 + Q \cdot \varepsilon^n$$  \hspace{1cm} (1)

where $\sigma(\varepsilon)$ - stress, MPa; $\varepsilon$ - strain; $Q$ - hardening index; $\sigma_0$-yield strength, MPa. In accordance with the stage of the plastic flow, the parabolic index n takes the following values: n=0 at the yield plateau, n=1 at the stage of linear strain hardening, n=1/2 at the stage of parabolic hardening. In the field of working deformation during thermal power treatment, this index is in the range and $0 \leq n \leq 1/2$.

At each stage of the plastic flow, a certain pattern of localization of plastic deformation is formed. At the stage of yield plateau there is a movement of front separating elastically and plastically deformed volumes. At the stage of linear deformation hardening, there is a movement of several localized plastic deformation zones with constant spacing between them with an increase in their number by the end of the stage (from 2-3 to 5-10). At the stage of parabolic deformation hardening, a stationary system of plastic deformation zones is formed. At the stage of prefailure, the plastic deformation zones merge with the formation of a stationary neck. When moving from one stage of the plastic flow to another, the localization pattern is rebuilt through its destruction, randomization of plastic autowaves and the formation of a new pattern.
It is obvious that the coefficient of locality or localization parameter under tension of cylindrical specimens, in addition to the influence of errors in diametric dimensions, initial curvature, and heterogeneity of material properties, will be determined by the stage of strain hardening reached in each of the experiments. During thermal force treatment, the temperature effect on the hardening curve should be taken into account when heating the workpieces. The aim of the study is to determine the loading parameters of the workpiece taking into account the stage of plastic flow, where the degree of uniformity of deformation will be maximum value.

3. Experimental technique

Experimental studies on the technology of thermal power treatment to study the uniformity of deformation were carried out for samples of alloy 12Cr18Ni10Ti. The tests were carried out on the installation for thermal processing for stretching using a heating device and a controlled load mechanism. In each experiment, three factors are constant: the heating rate to the working temperature, the working temperature, and the cooling rate to room temperature. Two factors are variable: the strain and the strain rate. The heating temperature of the workpiece is $T=300^\circ$C. Physical and mechanical properties of 12Cr18Ni10Ti at 300$^\circ$C are next: the elastic modulus $E=1.9\times10^5$ MPa, yield strength $\sigma_s=160$ MPa and the coefficient of linear expansion $\alpha=17.2\times10^{-6}$ 1$^\circ$/C. The strain value $\varepsilon$ was set in the range from 0.34% to 6%. The loading rate was 0.0534 mm/s and 0.00457 mm/s. Stretching to the maximum degrees of deformation was carried out only at a low loading rate due to the strong speed effect on the deformation resistance.

The samples were a rod with a length of the deformable part of 1200 mm and a diameter of 30 mm. The number of samples for testing is 16 pieces. On each sample, 20 notches were applied every 60 0,01 mm, 0,2-0,4 mm deep. Before testing, the distance between adjacent risks was measured. The test cycle was consisted from heating the sample to $T=300^\circ$C. In this case, the temperature strain is 0.39% which corresponds to an absolute elongation of 4.97 mm. After heating, stretching at a given speed to a set strain value was performed. After that, cooling to $T=20^\circ$C was carried out. In the end, the distance between adjacent risks was measured again.

To characterize the degree of deformation uniformity along the sample length, a localization parameter of two types is introduced. Evaluation of uniformity by two parameters is carried out in connection with the characteristics of the deformation process by two factors: the average level of strain and strain variation on the marked areas of the sample. The localization parameter of the first type $L_a$ was determined by the formula:

$$L_a = \frac{\varepsilon_{i\text{max}}}{\varepsilon_a}$$  \hspace{1cm} (2)

where $\varepsilon_a$ is the average strain on the marked sections of the sample; $\varepsilon_{i\text{max}}$ - maximum strain of the $i$-th rod section in each test. The localization parameter of the second type $L_{\text{max}}$ was determined by the formula:

$$L_{\text{max}} = \frac{\varepsilon_{i\text{max}}}{\varepsilon_{i\text{min}}}$$  \hspace{1cm} (3)

where $\varepsilon_{i\text{min}}$ is the minimum strain of the $i$-th rod section in each test.

The section provides data on the locality coefficients of two types, measured on samples after stretching at different speeds to various degrees of deformation. Total strain is the sum of the temperature, plastic and elastic components. To obtain load strain, the temperature part of the strain was subtracted from the total one. When testing at the installation, there was an error in ensuring exactly the specified value of deformation due to the error and uneven heating of the sample, deformation and slippage in the grips of the device. To determine the stage of curve at which the sample was in the test,
the values of load strain were used. It was obtained by adding the elastic component of the deformation to the intersection with the loading curve.

The graph of the hardening curve obtained on a tensile testing machine is shown in figure 1 with the stages of plastic flow. To determine the position of the characteristic sections of the hardening curves, control points are used – yield strength, transitions to the linear hardening section and to the parabolic hardening stages. Control points on the chart: stage 1 (points 1-2) – yield point – 0 – 0.3%; stage 2 (points 2-3) – linear hardening – 0.3 – 1.87%; stage 3 (points 3-4) – parabolic hardening-more than 1.87%.

The grouping of the localization parameters was carried out in three classes depending on the stages of the hardening curve where the workpiece was located at the end of the loading cycle in a particular test. The results of grouping the localization parameters in the figure 2-4 in the form of a box plot. Whiskers are extremes value, a point is outliers, and a rectangle defines the edges between which from 25% to 75% of the data is located. The line inside the rectangle is the median of the group values.

4. Research results

The explanation of obtained distributions may lie in the fact that in addition to the initial non-uniform properties, plastic strain localizations along the shaft axis can be determined by the wave pattern of propagation of plastic flow. The obtained distributions of elongations over the sections have a periodic character, especially on stage 2 and 3. The obtained distributions of elongations over the sections have a periodic character with deviations. If the autowave length $\lambda$ is estimated from [4], it is proportional to the sample length $l$

$$\lambda = k \cdot \ln \frac{l}{l_0}$$

Where $k$ is the scale factor; $l_0$ is the minimum length of the sample in which the autowave of the plastic flow is formed. Estimation using this formula shows a wavelength of about 34.5 mm. In the measured sections, approximately two waves are placed. The dispersion of wave parameters affects the estimation of the locality coefficient. Also the discrete character of deformations measurements on control sections introduces the error in an assessment of uniformity of sample stretching.

**Figure 1.** Strain-stress curve for alloy 12Cr18Ni10Ti at 300°C.

**Figure 2.** Grouping by classes depending on the stage of the hardening curve for the localization parameter of the first type: 1- yield plateau, 2-linear hardening stage; 3-parabolic hardening stage.
Figure 3. Grouping by classes depending on the stage of the hardening curve for the localization parameter of the second type: 1 - yield plateau, 2 - linear hardening stage; 3 - parabolic hardening stage.

Figure 4. Grouping by classes depending on the stage of the hardening curve for the localization parameter of the first type with subdivision by subgroups of deformation rates: low high.

The Kruskal-Wallis nonparametric test was used to check the coincidence of the mean values of grouped localization parameters for the corresponding loading stages. The following data were obtained for the localization parameter of the first type: chi-squared 5,7857 at degrees of freedom df=2 and the significance level p-value=0,05542, for the localization parameter of the second type chi-squared 5,8333, df=2, p-value=0,05411. Since the obtained criterions are higher than the critical values for these conditions, the statistical difference of the means in all compared groups is determined. When comparing data for stages 2 and 3 grouped by low loading rates (figure 4), the Wilksinson – Mann test did not show statistical difference. This is due to the large correspondence between the loading rate and the plastic flow rate in the formation of autowaves, which allows to form a more uniform picture of the deformation distribution over the sections.

At the second stage of the stress-train curve, with the growth of the average strain, the difference between the extreme values of deformations decreases due to the formation of an increasing number of mobile zones of localized plasticity. At the third stage, the zones of localized plasticity formed at the previous stage pass into the stationary mode. As the total strain increases further, the difference between the extreme strain values in sections decreases.

Stretching during thermal force treatment of workpieces with deformation exceeding the maximum value achieved in the studies does not make sense for several reasons. First, it is the subsequent transition to the last stage – the formation of a stable neck and the growth of heterogeneity of localization due to the convergence of zones of localized plasticity in one point. Secondly, the growth of deformation is accompanied by an increase in material defects – the growth of dislocation density, further growth of deformation texture. For the operating conditions of parts that are usually machined by this method, this can have a negative effect. Since the features of the deformation structure contribute to a decrease in corrosion resistance, it negatively manifests itself for parts operating at high temperatures.

5. Conclusions
All plastic deformation localities have been previously associated with the heterogeneity of the properties of the workpiece material. It is necessary to take into account that the experimental studies
are carried out on the prepared samples, mechanically processed to a high degree of accuracy and usually small in size. The technology of thermal force treatment was tested on blanks with a length up to 6 meters, and the workpiece itself was not processed at all except for the parts on the edges under the grips. Dimensional accuracy and shape error, properties of the workpiece material corresponding to the parameters of the rolled create additional disturbing factors for the formation of the stress-strain state. A wide variety of materials, standard sizes of axisymmetric parts, shapes and ratios of their lengths and diameters complicates the picture of the formation of plastic flow localization. But as noted in [5], beyond fluidity limits for different materials and alloys, there is a commonality in the formation of wave patterns of plasticity localization.

Questions of localization in fundamental researches are considered on the prepared flat samples with small length of deformable part. This is done to enable the use of speckle photography of displacement fields. Here was an assessment of the localization pattern after the completion of the deformation cycle. Due to the use of heating devices, the size and shape of the samples, it is not possible to use high-precision displacement control methods. In normal production conditions, the requirements for high precision dimensions, shapes, including straightness to ensure the preliminary stages of their production technology is not possible. This also applies to the error of diametrical dimensions in long blanks and the initial curvature of their axis.

Taking into account the uneven heating of the workpiece, its non-stationary nature, finite and variable stiffness of the grips and the entire installation, it is difficult to ensure exactly required degree of deformation with high accuracy to the desired point of the plastic flow curve, where the picture of the formation of autowaves satisfies us in terms of uniformity. The technology of thermal force treatment has a feature of the temperature regime, which is that for a full cycle of processing it changes from the initial to the working and back. The nature of the localized plasticity patterns will be complicated due to the temperature shift of the plastic flow curves and the change of hardening stages due to this phenomenon. Getting into the zone of transients between the flow stages also increases the probability of forming an uneven pattern of elongation of the sections. All these issues require additional research in order to use the proposed technology with high efficiency and reliability.

References
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