Evaluation of the uniformity of plastic deformation under tension

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Abstract. The article deals with the method of estimating the uniformity of the axial strain distribution under tension of cylindrical samples. Such an assessment is necessary in the design and conduct of thermal power treatment within the procurement stage of the technological process. The technology of processing of low-rigid long-length blanks, which consists in simultaneous heating and deformation, mainly by stretching, is considered. This method provides the formation of straightness of the workpiece with alignment and reduction of residual process stresses. For long-length workpieces, the distribution of deformations in the axial direction across different zones is unstable. It is associated with the initial heterogeneity of the material properties, uneven heating and autowave nature of the plastic flow. A technique is considered that provides a comprehensive assessment of the uniformity of stretching along the length with sufficient simplicity and high objectivity. The results of using the developed integrated assessment for high-temperature tension of samples made of corrosion resistant alloy are presented.

1. Introduction
Modern technological equipment (machines, pumps, chemical devices, tooling, etc.) is characterized by high productivity, significant speed of rectilinear movements of working bodies and high speed of rotation of units and parts. More and more parts in such loaded, high-speed machines have minimal material consumption and, by design features, belong to the class of non-rigid. A separate class of parts - running shafts and screws. The accuracy of their work depends on the uniformity of the axial pitch of the threads. But relaxation processes in the workpiece material lead to a loss in the accuracy of the thread in a step due to spontaneous deformation processes in the axial direction.

The technology of thermal power treatment was developed, which consists in the simultaneous application of axial load and heating of the workpiece. This treatment is performed in one cycle of heating - exposure - cooling. The purpose of processing is to reduce and equalize residual technological stresses in the longitudinal and transverse directions of a long part with the simultaneous formation of a rectilinear geometry of the workpiece. This is possible when the elongation of the workpiece exceeds the yield strength, and this value strongly depends on the initial curvature of the workpiece. To ensure uniform deformation along the entire length, it is necessary to solve the problem under which parameters and the laws of their changes to conduct thermal power treatment. These include the heating temperature, heating and cooling rates, exposure time, strain value and strain rate. The main of these parameters is the strain value.
The degree and nature of the localization of strain along the length is determined by the properties of the material, which have a probabilistic distribution of parameters (yield strength, elastic modulus, coefficient of linear expansion), the state of the surface layer, and the initial geometric accuracy (unevenness of diametric dimensions, deviation from straightness).

It is necessary to study the dependence of strain localization, including that associated with autowave processes, which are the result of self-organizing deformation processes at micro- and mesoscales. For this, it is necessary to evaluate the general pattern of the distribution of plastic deformations obtained by studying the influence of the state of the surface layer, the initial curvature of the workpiece, and the stages of plastic deformation and taking into account the temperature effects. It is necessary to assess the degree of homogeneity of plastic deformations along the length of the sample. And this evaluation parameter is necessary to determine the effectiveness of thermal power treatment in terms of ensuring and maintaining the accuracy of sizes and shapes in accordance with the stages of its manufacturing technology and during the operational period.

2. Actuality

The reason for the disturbance of the internal equilibrium state of the workpiece, which reveals itself in the form of warpage, is structural, temperature, and force non-homogeneity during processing. There is a relationship in the form of a sequence of processes: heterogeneity of deformations along the length, unstable diametrical size along the length with variable physical and mechanical properties, variable processing conditions, loss of accuracy and violation of uniformity. Therefore, along with the level and distribution of residual stresses, it is necessary to form a stable geometry due to the uniformity of strain.

In order to ensure uniform strain, it must be evaluated. Issues of assessing the localization of strain under tension were considered earlier [1].

For this purpose, localization coefficients were introduced. The localization coefficient $L_1$ of the first type was determined by the formula:

$$L_1 = \frac{\varepsilon_{i_{\text{max}}}}{\varepsilon_{\text{mean}}},$$

where $\varepsilon_{\text{mean}}$ 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 coefficient of the second type $L_2$ was determined by the formula:

$$L_2 = \frac{\varepsilon_{i_{\text{max}}}}{\varepsilon_{i_{\text{min}}}},$$

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

There are two drawbacks to this assessment. The strain uniformity is characterized without taking into account the nature of their distribution along the length, i.e. simply the difference across the entire measurement base is estimated. Also, due to the growing denominators with increasing deformation, the coefficients will decrease, even without changing the parameter in the numerator. It also violates the objectivity of the process assessment.

In [2], when studying the localization of the plastic flow of flat samples, the degree of macrolocalization versus time was estimated using, in fact, a modification of criterion (1), the coefficient of plastic strain non-uniformity

$$k = \frac{\varepsilon_{yy_{\text{max}}}}{\varepsilon_{yy_{\text{mean}}}}.$$
where $\varepsilon_{yy}^{\text{max}}$ is the maximum longitudinal deformation; $\varepsilon_{yy}^{\text{mean}}$ - mean strain. And the value of this parameter in a wave-like manner increases over time. In [3], under tension and torsion of samples with the length of the working part varying from 12 to 64 mm, a strain field was obtained during digital video recording. According to the results of the analysis, the distributions of longitudinal strains are formed, which have a symmetrical character of the same type for samples of various lengths. The measurement base was determined by the capture area during surveying, the resolution of the hardware and the features of the software that generated the picture of the distribution of deformations.

The study of regularities in the formation of technological features of the localization of plastic flow is necessary to assess the subsequent uneven distribution of the allowance for processing, to determine the regularities of the formation of inhomogeneous stress-strain state at the macro level. Evaluation of strain at the mesoscale, as a rule, of flat samples, with a small base for measuring the displacement field, is of little use for solving real production problems. To improve the efficiency of workpiece processing in the framework of thermosilic processing the results of such studies are not yet very actual and have more theoretical significance. The characteristic wavelength size of autowave plastic flow processes is several millimeters [4]. A more close to production conditions, a comprehensive assessment of the uniformity of plastic strain is given in [5]. It is based on the distribution density of the main elastoplastic deformations, their intensities, random Nadai-Lode coefficients.

All of these works have a material science aspect; all of them are carried out on flat samples with a limited length of the deformable part. The localization of plastic deformations is considered at the mesoscopic level, rarely generalizing to macroscopic scales. For technological purposes, it is necessary to identify the features of the formation of localization of plastic strains on a macro scale, preferably, taking into account mesoscopic patterns of the distribution of strains. The paper develops a method for estimating the uniformity of the distribution of strain along the sample axis and an example of its application to the analysis of typical patterns of deformation localization taking into account the stages of plastic flow.

3. Experimental technique

To assess the degree of uniformity of tensile strains, it is proposed to determine the locality coefficients of two types. In addition, after subtracting the average deformation from the total deformation from the measured zones it is proposed to determine the accumulated difference of the strain in neighboring areas as standard deviation, strain total amplitude and to build and evaluate a histogram of the distribution of strain on zones in the parameters skewness and kurtosis, as well as to check the conformity of the obtained experimental distribution normal. To test the proposed parameters, signals were generated simulating various strain distributions along the axis of the sample. Further, based on these data, the proposed estimates are obtained. The signals corresponded to the following generated test signals: 1 - the sum of two harmonic signals with different frequencies and amplitudes; 2 – pure harmonic signal with one mode; 3 - the sum of two harmonic signals with different frequencies and amplitudes with the addition of noise with a normal distribution and zero mean; 4 - the sum of the harmonic signal with a constant frequency and a signal with a variable frequency; 5 - the sum of the harmonic and pulsed signals.

The proposed methodology for assessing the localization of plastic flow is applied to the results of studies on the stretching of samples from 12Cr18N10Ti alloy in a thermal power treatment operation. A sample bar had next dimensions: a length of the deformable part of 1200 mm and a diameter of 30 mm. On each sample, 20 notches were applied every 60–0.01 mm, with a depth of 0.2–0.4 mm, and a width of 0.5–1 mm. Before testing, the distance between adjacent risks was measured. The test cycle consisted in heating the sample to $T=300^\circ$ C, then stretching at a given speed and magnitude, followed by cooling to $T=20^\circ$ C. After that, the distances between neighboring risks were measured again.
4. Research results

An example of the results of the evaluation of test data is shown in figures 1-4. The original strain distribution is shown in figures 1,2, and figures 3,4 show a histogram with a probability density graph and a box plot indicating interquartile range (IQR) and median.

![Figure 1. Test signal №1.](image1)

![Figure 2. Test signal №4.](image2)

![Figure 3. Test signal evaluation №1.](image3)

![Figure 4. Test signal evaluation №4.](image4)

The table 1 shows the parameters for evaluating the test signals. From the point of view of evaluating precisely the uniformity of the distribution of strain along the length, their periodicity, stability, and total value, the most informative are the interquartile range IQR, kurtosis for estimating outliers, and the degree of compliance of normality with respect to W and p-value of the Shapiro-Wilk test. The following parameters are less indicative: mean value, standard deviation, locality criterion of the first and second types, skewness for estimating distribution asymmetry. These all estimates together form a set of features that can be used to characterize the stretching process.

|   | Mean | Sd  | IQR  | Skewness | Kurtosis | W    | p-value | $L_1$ | $L_2$ |
|---|------|-----|------|----------|----------|------|---------|-------|-------|
| 1 | 2.37 | 0.34 | 0.409594 | -0.353919 | -0.32047 | 0.96654 | 0.6558 | 1.31  | 1.85  |
| 2 | 1.03 | 0.36 | 0.65329 | -0.06671 | -1.53624 | 0.90245 | 0.03904 | 1.47  | 2.99  |
| 3 | 2.03 | 0.36 | 0.59853 | 0.041886 | -1.00303 | 0.95045 | 0.3474 | 1.36  | 2.23  |
| 4 | 1.27 | 0.69 | 0.807873 | -0.68064 | -0.42841 | 0.90381 | 0.04151 | 1.72  | 22.62 |
| 5 | 1.28 | 0.72 | 0.60642 | 1.864662 | 3.741977 | 0.77991 | 0.00033 | 2.59  | 6.45  |
For each stage of the plastic flow for the 12X18H10T alloy, typical localization graphs are shown in figures 5-8 and their estimates are given in table 2. To determine the position of the characteristic sections of the hardening curves, control points are used - yield strength, transition to the linear hardening and parabolic. Control points on the plastic flow curve: Stage 1 — yield point — 0–0.3%; Stage 2 - linear hardening - 0.3 - 1.87%; Stage 3 - parabolic hardening - more than 1.87%.

**Table 2.** Evaluation of the distribution of strains under tension of samples of alloy 12Cr18N10Ti.

|       | Mean | Sd    | IQR  | Skewness | Kurtosis | W     | p-value | L₁    | L₂    |
|-------|------|-------|------|----------|----------|-------|---------|-------|-------|
| 1 stage| 0,42 | 0,189 | 0,22 | -0,6803  | 0,94706  | 0,4117 | 2,27    | 55    |
| 2 stage| 1,63 | 0,337 | 0,57 | -1,0101  | 0,94481  | 0,3495 | 1,32    | 2,15  |
| 3 stage| 4,23 | 0,382 | 0,455| -0,06134 | 0,234033 | 0,99383| 1       | 1,18  | 1,46  |

The distribution of strain of the first stage is characterized by the presence of a burst. This may be due to the formation of the Luders band [6-8]. Generally, stable in terms of quadratic deviation and locality coefficients, it is inferior in uniformity to the distribution of strain of the sample corresponding to the third stage of processing — the parabolic hardening section. At this stage, the assessment gives the following: the interquartile range is more symmetrical, the median is closer to the center, and the distribution of deformations is more consistent with normal. Despite the large spread in comparison with the first sample, this distribution is more uniform in terms of spatial structure formation.

**Figure 5.** Assessment of the distribution of the first and third stages of plastic flow in the first stage.

**Figure 6.** Assessment of the distribution of the first and third stages of plastic flow in the third stage.

**Figure 7.** Assessment of the distribution of the...
first and third stages of plastic flow.

For the second stage, the characteristics are inferior to the first and third stages. Such an assessment is typical for all samples. This may be due to the features of the localization of deformation at the stages of plastic flow. The second stage of linear hardening is characterized by the formation of new fronts of plastic flow from one at the end of the first stage to 5-10 at the end of the second. Owing to these new fronts, the third stage is characterized by the alignment of strains along the sample length. Processing with a minimum amount of deformation within the first stage is not effective in terms of working out the entire volume of the workpiece, eliminating its curvature, and balancing stresses over sections.

5. Results and conclusion

The paper discusses the methodology for assessing the uniformity of plastic deformation for workpieces processed within the framework of thermal power technology. To assess the degree of strain unevenness along the length, parameters were proposed that were approved on test data. It includes the determination of the locality coefficients of two types, the cumulative difference of the strains in neighboring sections in the mean square sum, as well as the construction and estimation of histograms of the strains distribution. On test data that simulate the different pattern of the strain distribution along the length, examples of the application of such a technique were given. Then, the evaluation technique was applied when stretching cylindrical rods from 12Cr18N10Ti alloy as part of thermal power treatment. When analyzing the experimental data, estimates of the strain uniformity were determined for the samples and grouped in accordance with the stages of plastic flow to which the corresponding samples were deformed. Various characteristic features of the plastic strain distribution clearly corresponded to certain stages of the plastic flow, and this is manifested in the proposed estimates.

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