Improving the accuracy of axisymmetric parts by applying controlled heat treatment

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Abstract. The article discusses the technology of thermal power treatment of long, non-rigid parts of the “shaft” type. The design of the device for thermal-power deformation of the shaft and the principle of its operation are given. The device is equipped with a three-circuit automatic control system. The control system allows you to control the forces for axial deformation and the temperature of heating and cooling. The developed technology allows us to solve the problem of maintaining the straightness of the shaft during operation.

1. Introduction
High requirements for operational accuracy of axisymmetric parts (“shaft” type) with small rigidity are a trend in modern mechanical engineering associated with a decrease in their metal consumption and increase in rotational speed. The residual deformation of the shafts of low rigidity is associated with a violation of the balancing stress state of the workpiece, which occurs during the machining process. This is manifested after the end of the process with a significant lag in time [1.8-11].

The dominant factor in the formation of the error of the shafts is the warping of the shafts as a result of an uneven distribution of residual stresses [1-15]. Simulation of the operation of thermal power treatment (TPT) and analytical studies [6-8] showed that the value of deformations of low-rigid parts of the “shaft” type can be determined even during the creation of the technological process and indicate the corresponding minimum allowances for processing.

2. Relevance of work
The task to which this development is aimed is to improve the quality of workmanship of non-rigid axisymmetric parts with the following results:

• increasing the stability of the size and shape of long, non-rigid axisymmetric parts by eliminating the incompatibility of elastic axial residual deformations during unloading;
• liquidation of technological heredity due to a complete restructuring of the material texture with multidirectional applied external tensile-compression forces of the zones of the deformed piots of the part;
• elimination of the influence of axial external forces due to the loose ends of the part;
• elimination of the influence of zones of rigid grips on the focus of axial residual stresses.

Goal. Improving the stability of size and shape by eliminating directionality and minimizing the level of axial residual stresses. To achieve this goal, a technology and an automatic thermal power control system have been developed.
3. Presentation of the main material
Consider the mechanics of the process of elastoplastic deformation of axisymmetric parts of the "shaft" type. The load-unloading diagram without taking into account the heating temperature is shown in Fig.1.

To control the residual stresses, one must know how they arise [1-11]. Let us consider the cause of residual stresses from the point of view of deformation mechanics using the example of one-dimensional deformation, without taking temperature into account. If stress $\sigma_p$ is applied to the shaft and unloading is performed (Fig. 1), then at the moment of unloading start, stress $\sigma_p$ and strain $\varepsilon_1$ exist in the metal. We believe that the elastic unloading occurs according to the linear law in the diagram "stress - strain". Then elastic deformations are determined by Hooke's law

$$\varepsilon_2 = \frac{\sigma_p}{E}.$$  

(1)

Here $E$ is the modulus of elasticity. As a result of unloading, the residual stress and the corresponding elastic residual strains are determined as $\varepsilon_4 = \sigma_{ost} / E$, and the strain

$$\varepsilon_3 = \frac{\sigma_{ost} - \sigma_p}{E}.$$  

(2)

Since the unloading process corresponds to them, the deformation at the time of complete unloading

$$\varepsilon_4 = \varepsilon_2 + \varepsilon_3.$$  

(3)

Suppose that $\sigma_{ost} = 0$. Then from (1) it follows $\varepsilon_2 = - \frac{\sigma_p}{E}$. From a comparison of (1) and (3) it follows

$$\varepsilon_2 = - \varepsilon_3.$$  

(4)

Since the strains $\varepsilon_3$ are always compatible, from (4) follows the compatibility of the elastic strains $\varepsilon_2$ at the moment of complete unloading. This means that after unloading, residual stresses and elastic residual strains remain, and elastic strains before unloading are not compatible.

\[ Figure 1. \ Deformation \ diagram. \]

Here: $\varepsilon_1$ - elastoplastic deformation; $\varepsilon_2$ - elastic deformation; $\varepsilon_3$ — elastic deformation after unloading; $\varepsilon_4$ — elastic residual deformation; $\varepsilon_5$ - plastic deformation; $\sigma_p$ - operating voltage; $\sigma_{ost}$ - residual voltage after unloading
To solve the problem of compatibility of elastic deformations during unloading, a technology has been developed for the process of thermo-power processing of axisymmetric parts, including threading on its surface along the entire length and laying on a horizontal roller conveyor. By means of a controlled worm drive of axial displacements, the workpiece is automatically screwed into the hollow cylinder of the hydraulic power drive rod through screw clamps.

Next, the section between the grips is heated to the tempering temperature in the zone of weak dependence of the tensile strength on the heating temperature and axial tensile forces are applied to both ends of the sections in opposite directions. Tensile is produced by the value of plastic deformation equal to (0.8-1)\% using an automatic control system.

The value of the specified plastic deformation is controlled taking into account the thermal expansion and, when the specified value is reached, the dwell is realized according to the holiday regulations. Next, the amount of plastic deformation is measured, the heat source is turned off and unloading is performed by reducing the axial tensile forces in each section in proportion to the rate of decrease of the cooling temperature to ambient temperature.

The values of elastic residual deformations in both deformed parts of the part are measured and compared with elastic deformation before unloading. When they are incompatible, additional loading is carried out with the application of compression forces. The load-unloading cycle is repeated, starting with the magnitude of the underload force. If the elastic residual strains and elastic strains are equal before unloading in each section, the deformation process is stopped and then the part is subsequently deformed over the entire length according to the same algorithm.

Device for thermo-power treatment includes an automatic control system (ACS), which contains:

- two linear displacement sensors included in the feedback of the control loop of the plastic deformation of the sections;
- two independently working hydraulic power axial deformation drives. ACS is made with the ability to control the working pressure in the chambers of the power cylinders using controlled chokes.

Power cylinders have feedbacks using pressure sensors and diagnostics of the heating temperature of the workpiece section. The ACS contains two control loops: the first loop includes two control channels for axial plastic deformation of the workpiece section, and the second includes a control channel for the heating temperature of the zone of the treated section. Each control loop contains axial strain and temperature sensors included in the feedback loops of the control unit.

Installation for axial deformation of the workpiece contains a horizontal roller conveyor for positioning and supplying the workpiece to the working area. The controlled axial feed drive includes:

- a reverse electric drive;
- a worm gear with a hollow shaft with an internal thread which is mounted in the hub of the worm wheel. A prismatic spline is installed on its outer surface, which allows the workpiece to move freely under temperature and force effects.

The hydraulic power drive is equipped on both sides with grips mounted on the butts of the moving rods of the hydraulic power drive. Cylindrical rings with internal thread for screwing in the workpiece are built into the gripper bodies. Rings have a thickness equal to ten threads of the thread and are used for reverse axial deformation. The number of rings is selected depending on the strength of the workpiece material.

Fig. 2 shows a general view of the device, and Fig. 3 shows a general sectional view of the power drive and a functional diagram of automatic control.
Device for implementing the technology of thermal power treatment of long axisymmetric parts contains: body 1, made prefabricated in the form of two cylinders 2 and 21, which are separated by a rigid ring 3; two covers 4 and 41; two hollow plunger rods 5 and 51, the chambers of which 6, 61 and 7, 71 are insulated on both sides with elastic seals.

A cylinder 8 is inserted into the internal holes of the plunger rods 5 and 51, on the outer surface of which there is a ring 3 that separates the two power chambers. A heat insulator 9 is fixed on the inner surface. The cylinder 8 is fixed relative to the covers 4 and 41 with pins 10 to limit the stroke of the plunger rods 5 and 51.

Grooves 11 are made in the rods, and grips 12 and 121 are attached to the ends of the plunger rods 5 and 51. Rings with an internal thread 13 and 131 have the function of fixing the deformation section of the part. Reverse rings 14-141 provide the reverse of deformation. The covers 15-151 of the housings 12-121 carry out a force closure of the rings.

ACS includes three control circuits and consists of a control unit 17, two outputs of which are connected to the inputs of two identical channels, consisting of two series-connected units 18 and 181 and 19 and 191. Blocks 18 and 181 are controlled chokes, one of whose outputs the inputs of the pressure sensors 20 and 201 are connected (feedback of the control unit 17). Blocks 19 and 191 are
electrohydroconverters, one of the inputs of which the outputs of the control unit are connected 17. The outputs of the linear displacement sensors 21 and 21\(^1\) are connected with the input of the control unit 17.

These sensors are mounted on the covers 4 and 4\(^1\) with gaps \(\Delta 1\) and \(\Delta 2\) relative to the movable piston rods 5 and 5\(^1\). The output from the blocks 19 and 19\(^1\) is connected to the chambers of the hydraulic power cylinder. The shaft ends of the piston rods are made in the form of a sector of a circle of radius \(r\). The second unloading chambers are made with a sector of radius \(R\). The working pressure is supplied to the power chambers through openings 24 and 24\(^1\). The third control circuit consists of a control unit 17, one of the outputs of which is connected to the input of the DC power supply 23. Its outputs are connected to the workpiece with the help of strong clips. The temperature sensor 22 is mounted on the body 1 and is included in the feedback loop.

Device works as follows. The workpiece 16 is machined before the thermal power machining on a lathe using self-centering lunettes and a thread is cut. Next, it is laid on the rollers 24 of the conveyor 23 and put into engagement with the grippers 12 and 12\(^1\) of the hydraulic power drive 1. The number of threaded rings 13, 13\(^1\) and the length of the deformation of the processing zone are calculated as a function of the coefficient of technological rigidity of the part \((K = l / d = 5-8)\) and strength properties of the material.

According to the algorithm of the ACS, the third heating and cooling control circuit of the selected part section is turned on. The output signal from the control unit 17 is supplied to a direct current source 23. The heating of the section is controlled by a temperature sensor 22, the output of which is included in the feedback of the heating and cooling temperature control loop. Heating is carried out in tempering mode according to the heat treatment technology of the selected material.

The heating of the part area is carried out until temperatures are reached with a weak dependence of the force on deformation.

This is followed by exposure according to the technology of heat treatment of tempering and the second control loop of the elastic-plastic deformation is turned on. Block 17 provides a control signal to gearboxes 18 and 18\(^1\): The pressure in the gearboxes is transmitted from the pump station, which is not shown in Fig. 3. The pressure is set in advance as a function of the physicomechanical properties of the deformable material.

Monitoring of working pressure is established using pressure sensors 20 and 21\(^1\) included in the feedback of the pressure control channels. The control signals from the other two outputs of block 17 are fed to the inputs of the electrohydroconverters 19 and 19\(^1\), and the outputs of the latter are connected to the working cavities of the hydraulic actuator through openings 24 and 24\(^1\).

After the creation of the working pressure the central cavities of the cylinder diverge in different directions, creating a tensile deformation of the material of the workpiece using grippers 12 and 12\(^1\). The magnitude of the deformation of the treated zones are controlled by two linear displacement sensors 21 and 21\(^1\). They are mounted on the fixed covers 4 and 4\(^1\) of the body 2 relative racks mounted on the plunger rods 5 and 5\(^1\) with gaps \(\Delta 1\) and \(\Delta 2\). Electrohydroconverters 19 and 19\(^1\) redistribute the pressure of the working fluid in the chambers of the hydraulic cylinders, and when the treated sections are cooled, the working pressure enters the end chambers. In the central chambers, pressure is released. The result is a process of loads in the treated areas of the part. After deformation of the entire workpiece, the reverse of the worm drive is turned on and the workpiece is moved to its original position.

4. Conclusions

The advantage of the developed technology allows you to: control the heating of the deformation sections of the workpiece; reduce the tensile strength of the material of the workpiece and the magnitude of the force; reduce the power and dimensions of the power drive. Simultaneous heating and alternating plastic axial deformation create a homogeneous structure of the material of the part. Control of temperature exposure is an effective tool in the zone of weak dependence of the elastic stress limit on deformation, stabilization and minimization of residual stresses. The choice of the
design of the grippers for axial deformation in the form of removable housings allows you to fix the sections of the deformation of the part in a wide range and equalize stresses in the gripping zone.

Fixing the part on the roller conveyor allows you to automatically move the part and enter it into the hydraulic power drive through a controlled worm drive. In this case, the workpiece can move freely with axial deformation and heating, without creating additional compression forces from the supports.

The system of automatic control of the amount of deformation, taking into account the difference in the movement of the grippers, the elastoplastic deformation of the left and right zones, automatically equalizes the deformation of both zones. Therefore, it ensures uniform plastic deformation of both the treated section and the entire length of the workpiece. ACS controls the process of loading and unloading in accordance with the temperature, external forces and the values of residual elastic deformations, which ensures the compatibility of elastic deformations. ACS increases the efficiency of due to the operational control of the values of technological parameters as a function of the deformation process. During the experiment, the initial residual deformations as compared to standard technology, decreased 6–9 times for 12Kh18N10T steels and 5–6.3 times for 30X13 steel, the level of technological residual stresses was decreased 8.5-12.6 times.

The suggested technology by stretching stainless steel billets increases the stability of the shape of a non-rigid shaft. After carrying out these operations, the factor of shape change after the ninety days of exposure does not have a significant effect on the change in the straightness of the axis of low-rigid shafts. The residual deformations of samples 1300 mm long and 40 mm in diameter after thermal processing technology are reduced by 7-8 times compared with the initial deformations.

The authors are not aware of similar studies published in the literature either in Russia or abroad.

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