Geometric stability of stepped shafts by ribbing its surface

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Abstract. The article discusses the technology of manufacturing low-stiff long multistage shafts made of stainless steels. A feature of this technology is the cutting of annular cooling fins on the entire surface of the shaft blank during machining and their use in thermal operations and further to finishing turning. To implement the technology, self-centering steady rests with double rollers were used during machining.

In many modern units, machines and devices, critical low-rigidity parts (LRP) “shaft type” are used. The continuous growth of the production volume of the Moscow Railways is due to the improvement of strength calculations, the optimization of the shapes of parts and structures, a constant decrease in the metal consumption of products and the increasing production of precision machines. Disproportions in the design parameters of the LRP create serious technological difficulties in production, the main reasons for which are as follows:

- significant elastic and plastic deformations at all stages of processing, assembly and operation of parts;
- low vibration resistance and various flexibility of technological system elements;
- significant influence of technological heredity on the reliability of work;
- warpage of workpieces caused by uneven residual stresses introduced at all stages of processing;
- low heat resistance of parts. The negative effect of the listed factors in the manufacture of LR leads to a violation of technological bases, errors in the shape and size of parts, surface defects, limitation of cutting conditions, and ultimately to a decrease in the operational accuracy and reliability of LR [1-4, 6-11,14-15].

Traditional methods of processing are ineffective for the production of low rigidity parts, therefore, the issues of their manufacture in practice are solved by limiting processing modes, by introducing manual finishing operations, which does not guarantee the required quality of products. Therefore, the improvement of technological processes for the manufacture of LRP is an important task that increases production efficiency and the quality of engineering products. The aim of the work is to develop a technology for stabilizing the shape of low-stiff long stepped shafts by the method of simultaneous and uniform temperature distribution along the entire length of the stepped shaft during cooling.

The problem to be solved by the developed technology is to increase the operational accuracy of finished products with the achievement of the following results: increasing the stability of the dimensions and shape of low-stiff long shafts by eliminating technological inheritance during
machining, eliminating the incompatibility of elastic deformations with uniform cooling, which excludes residual deformations for the entire shaft exploitation period. This problem is solved by the fact that the technology includes:

- cold straightening by bending using ACS [12];
- heat treatment by stretching in the slipway [13] with an exit to the physical and mechanical properties of the metal;
- elimination of the influence of axial compression forces;
- increasing the stability of the shaft shapes due to the elimination of surface residual stresses remaining after rough machining;
- uniform and simultaneous cooling of all stages of the shaft blank.

This technology is based on heat treatment of low-stiff stepped shafts on the surface of which their surface is ribbed. Pre-calculate the surface areas of the annular ribs of the shaft sections and the surface areas of the shaft sections. The ratios of these areas are found starting from the largest diameter of the central part of the shaft, while ensuring the equality of these ratios in all parts of the shaft. According to the design parameters of the ribs, they are grinded onto the shaft blanks in the STsL on a lathe. Then they are machined, forming an equidistant profile of the workpiece, taking into account the calculated diameters of the ribs at each section of the shaft. Heat treatment is carried out in a shaft furnace according to the standard technology in the modes of quenching or tempering in a vertical position, reaching the specified mechanical properties of the metal. Next, finish turning of each section is carried out to the diameter specified by the drawing. Calculations are carried out on the assumption that the amount of heat transferred is proportional to the heat exchange surface area and the temperature difference between the shaft and the cooling medium.

\[ Q = \alpha S(t_v - t_{oc}) \]  

where \( \alpha \) is the heat transfer coefficient; \( S \) is the heat exchange area; \( t_v, t_{oc} \) is temperature of the shaft and the cooling medium.

To ensure the equality of heat fluxes at all stages of the shaft, it is necessary to observe the equality of the ratios of the surface areas of the ribs and the areas of the surfaces of the shaft on two adjacent stages, starting with the maximum step diameter and ending with the last minimum stage of the shaft blank.

\[ \frac{S_1}{V_1} = \frac{S_2}{V_2} \]

\[ S_1 = \frac{S_2V_2}{V_1} \]

\[ n = \frac{1}{t + t_1} \]  

Here \( S1, S2 \) are the total surface area of the ribs of two adjacent shaft steps; \( V_i, V_2 \) are surface areas of the shaft of the same steps; \( n \) is the number of ribs along the length of the step; \( t \) and \( t_1 \) – rib thickness and gap between them.

The \( S/V \) ratio at all stages should be constant. On small diameters, it is advisable to cut a triangular thread instead of rib grooves. The number of ribs is calculated in the following sequence. The area of one edge is calculated by the formula

\[ S = \frac{\pi}{2}(d - d_1)tC \]  

where \( d \) is the maximum rib diameter; \( d_1 \) – shaft diameter with allowance for finishing; \( t \) – rib thickness; \( t_1 \) is the size of the gap; \( C \) is the edge circumference.

The minimum thickness of the ribs and the gaps between them are determined by the processing technology and the need to transfer the amount of heat. Next, the total surface area of the ribs is calculated at the maximum diameter \( d \) of the shaft \( S = S \times n \) and then sequentially at all stages of the shaft.

For grooving the ribs, the blank of the shaft 1 is installed in the SCL 2, which are equipped with non-consumable electric hydraulic drives 3, figure 1.
The number of lunettes is calculated from the length of the shaft with a step equal to the ratio of length to diameter not more than ten. STsL are mounted on a separate bracket 4, fixed on the machine bed. The installed workpiece 1 in the STsL 2 is fixed along the X axis by two rigid centers 5 without the application of axial forces. The torque is transmitted through the drive chuck 6. The steady rest modes are controlled by the control unit 7. The longitudinal movement of the cutter group 8 is carried out by the drive 9, and the transverse feed of the cutters by the drive 10. A diagram of the basic operations of the shaft blank processing technology is shown in figure 2. Positions 1, 2, 4 in figure 2 are similar to positions in figure 1.

In the first operation, figure 2, the workpiece is machined along the outer surface in the STsL for the passage to create a base surface. This eliminates the need for centre hole machining and centering. Next, the operation of grooving the cooling fins is carried out. The depth of the groove is carried out to diameters d1 at all stages (diameter d1 is the size of the shaft with an allowance for finishing). The number of ribs is calculated by the formula (3) taking into account their thicknesses. Next, the ribs are grinded equidistantly to the shaft profile by the value of the maximum design rib diameter, forming the total surface of the ribs at all stages of the shaft. The finned shaft blank is heat-stabilized according to the technology. The equality of the S / V ratios at all stages of the shaft excludes non-simultaneous cooling and incompatibility of elastic deformations when cooling the shaft blank. Axial residual stresses are uniformly formed, which eliminates distortion of the shaft axis during operation. Further, finishing and operations are carried out according to standard technology: grinding of the bearing journals, milling of keyways, etc. All operations are carried out in the STsL on one machine with the replacement of the cutting tool holder with a milling and grinding head.

The novelty of the developed technology is unconventional machining of low-stiff shafts and a new method of stabilizing residual stresses based on the equality of the ratio of the surface areas of the ribs to the surface areas of the shaft at all its stages.

This technological method provides simultaneous and uniform cooling of all stages of the shaft. The processing of the shaft blank in the STsL installed at an interunit distance of no more than 10 diameters ensures high processing accuracy by increasing the technological rigidity of the "blank-support" subsystem, combining the bases, design and technological.

Basing the shaft blank in the STsL without compression by the rear centre eliminates the influence of axial compression forces and ensures the blank rotation around its theoretical axis.

The groove of the ribs provides interrupted cutting and eliminates directed heat flux, the latter minimizing the level of residual stresses at each stage.
Cooling of the shaft blank after heat treatment with finned surfaces ensures uniform cooling of all steps of the blank and, as a consequence, the compatibility of elastic deformations. The combination of elastic deformations ensures dimensional stability and the absence of warpage of the workpiece axis.

The ribbing of the surfaces of the shaft blank increases the processing efficiency by reducing the number of intermediate thermal operations.

In the course of the laboratory experiment, the initial residual deformations in comparison with the standard technology decreased by 3.4–4.6 times for 12Kh18N10T steels and by 3.2–4.3 times for 30Kh13 steel, the level of technological residual stresses decreased by 5.3–7.2 times. The factor of shape change with the course of six months of exposure does not significantly affect the change in the formed straightness of the axis of low-rigid shafts.

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