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Automatic Stabilization Systems of Non-Rigid Shafts in Turning Work

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***Abstract*—In present paper there is the refinement method of the non-rigid shafts turning work meant to be provided. There are foundations to the axial forces control necessity gained. The unit that outfits structured functional scheme of the self-centering rests (SCR) is presented. The main source of rests work by tool motion along the operated non-rigid shaft axis while the one is being centered to technologic shaft axis is widely described. There are operations conditions of the SCR hydraulic cylinders which allow one to level the replication of operated blank cross-section form examined. A planar design scheme of the subsystem "detail - support" taking into account the action of axial forces is presented. We also prove importance of the constriction axial forces due to temperature increase while operating. The integrated functional scheme of the Automatic Control Systems (ACS) is developed; it uses dynamometric system of the thermal deformation compensation. The axial sections profile records and non-rigid shaft circular profile records, taken after the turning operating, either with ACS applying or not, are represented here. It is shown that the error of processing is reduced 2-3 times.**

Keywords—non-rigid axisymmetric piece; automatic control system; materials operating precision

I. Introduction

Constantly increasing specifications for the precision of the operating of "shaft" type non-rigid axisymmetric pieces are supposed to be a tendency of mechanical engineering nowadays; a tendency which is related tightly to solid of reduction of the revolution's steel intensity, to increase of its rotary axis speed. The residual deformation of non-rigid shafts is connected with breakdown (during the mechanical processing) in the blank balancing tension; after the processing residual deformation appears with great time lag. The lack of the loss of the non-rigid shafts precision (while processing) multiplies examinations limits, merely the chance of the increase of the operating precision after mechanical [1-11] and thermomechanical [12-14] processing.

The present paper is devoted to the solving mechanical processing problems by control of axial forces of the blank constriction in turning work.

II. Relevance

The main influence on the precision of the non-rigid shafts operating is caused by a residual deformation in a form of shaft axis distortion that caused by the unbalanced axial component of residual stress. The instability of the tangency stress component leads to residual deformation in a form of the shaft cross-sections torsion near its axial; thus, the shaft does not lose straightness. The instability of radial stress components leads to residual deformation in a form of distortion of the circumference of the cross sections of the shaft [1]. The precision of the non-rigid long-measuring shafts depends only on the axial residual stress, which causes verily their axis distortion.

For the elimination of the non-rigid shafts deflection, the following and steady rests vary; the last ones process significant deficiencies, such as low capacity of the mechanical processing of the stepped shafts and total ignoring of dynamic events at subsystem "non-rigid shaft - support".

III. The Automatic Control System

For the elimination of the standard rests defects, there has been unit that outfits self-centering rests SCR [1] developed; they are clamped up to supports; supports are clamped up rigidly to bearer frame being positioned along all the axial slideways of the lathe unit. The structure of frame and supports in SCR is performed in a way to prevent any obstruction to the motion of support and tool. The structured functional scheme is represented in Fig. 1.

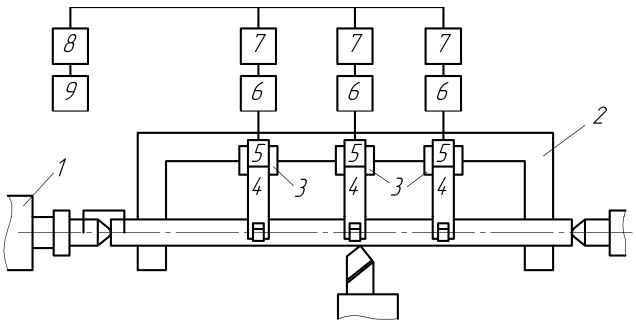

Fig. 1. The structured functional scheme (1 for lathe unit, 2 for beam supporting hydraulic rests and the drive, 3 for rests support arm, 4 for SCR, 5 for hydrocylinders, 6 for clamping force gates, 7 for controlled hydrodistributors, 8 for surplus valve, 9 for pump station).

The number of rests are placed either all along the blank depending on eq. rigidity in function of the piece sizes proportion (*1/d* < 5), or in the elements and antinode zones of the distribution of the main forms of pieces high vibrations. The SCR are placed at the flection vibrations elements; they are applying as eq. rigid supports. Thus, the pressure led to the SCR that provides piece clamping; however, controlled SCR of the isolator mode operating (setting on the surface not turned enough at the pass) generates pressure providing dampening of the vibrations.

It is quite necessary to admit that during the tool motion just along a shaft, the operation of the SCR changes the isolators mode to eq. rigid supports one. By initial conditions (just before the processing of the cutting) almost all of the SCR operate at the isolators mode; the rest of them operate at the eq. rigid mode which is set by the stockhead and the deadhead. These conditions are supported to centre piece axis relatively to technologic shaft axis; the piece supported elements are turned previously at the setting points of the back rest. There is a locating scheme unit of the blank (while operating) represented in Fig. 2.

The roll forming (in field of interaction with rests) decreases the forming error and provides the blank centering in front of the SCR theoretical centre. It is supposed to be the obvious dignity of the SCR. It is clear also that during the cutting at SCR zone, the processing kinematic conditions average indirectly out of reaction in a hydrocylinder to the deflection of cutting forces which is caused by operating of the rough tolerance vibrations, since the reactions at central tracer plate 1 and bars 2 are being added together on the hydrocylinder piston rod. Besides, if the blank exposed surface "ridge" clamps up sliding bar 1, then its applied force is high-average one, and the force applying from bars to hydrocylinder rod is low-average one; and vice versa. Sic resets, the Self-Centered Rest destructs the replication of a blank cross-section form. However, it founds rigid support of *d* size and provides fast approximation of a section form to the circle.

The blank beat at the rest zone by a rolled section was varied in range from 0.02 mm up to 0.08 mm after the first pass in experiments. After the second pass beat did not surpass 0.01 mm.

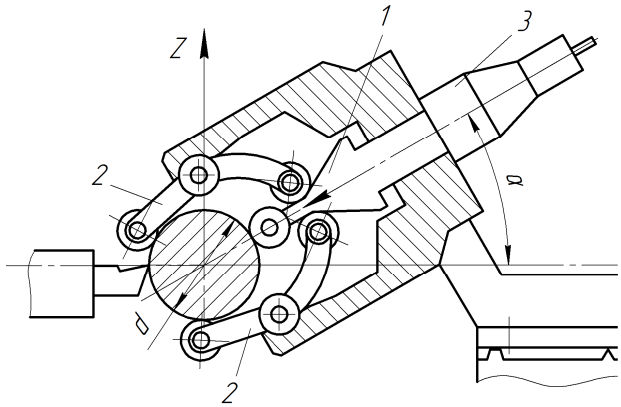

Fig. 2. The main profile of the Self-Centered Rest (1 for tracer plate, 2 for bars, 3 for hydraulic drive).

In such way, the applying of the shafts exposed surface in a form of support one by the SCR may avoid the replication of the non-circularity of a blank cross-section form.

Plus, after the work finishing, circularity variance gets 2-4 times lower in comparison with the shafts operating at three-jaw chuck and rear center/work driver center.

The significant dignity of the SCR applying (non-rigid pieces) in the processing is the following one. During the operating processing (taken almost on second pass), uniform tightness is forming (due to the depth permanency cutting); thus, there is eq. stress supposed to appear in piece parameters. The residual stress stability reduces the distortion of the non-rigid pieces; it also provides increase of its operating accuracy.

For the axial forces influence (while being processed), loading diagram is supposed to be shown as represented in Fig. 3.

With the temperature increase (during mechanical processing) the piece is being elongated; that causes merely extra constriction axial forces. To examine these forces we would disregard the influence of initial clamping forces and obtain the loading diagram represented in Fig. 3. The problem is insoluble statically; then, to obtain the axial force, we cite the deformation compatibility condition here:

$$\Delta l_T = \Delta l_g + \Delta l_{sp} \tag{1}$$

where Δl_T for piece thermal elongation, Δl_g for piece constriction by the created axial force influence, Δl_{SP} for supports clamping.

Obviously, we have to expand (1):

$$\alpha_T \Delta T l = \frac{S_{ex} l}{EF} + \alpha_{SP} S_{ex} \tag{2}$$

where ΔT for thermal increment, α_T for linear expanding temperature factor, S_{ex} for extra axial force, α_{SP} for supports axial yield.

An injecting parameter of piece axial yield:

$$\alpha_T \Delta T l = \frac{S_{ex} l}{EF} + \alpha_{SP} S_{ex}$$

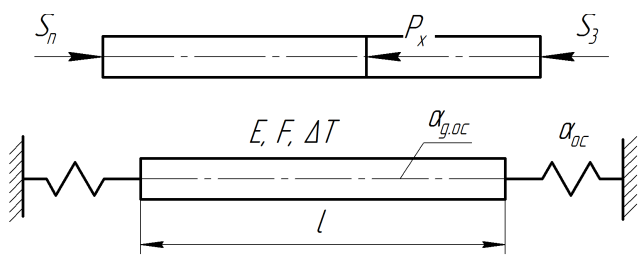

Fig. 3. Loading diagram of the subsystem "support-piece" acc. to axial forces.

We obtain:

$$S_{ex} = \frac{\alpha_T \Delta Tl}{\alpha_{goo} + \alpha_{SP}} = \frac{\alpha_T \Delta Tl \cdot EF}{l + \alpha_{SP} EF}. \quad (3)$$

As exploring shows, stockhead and deadhead axial yield values get varied over the range of (0.025-0.25)$\cdot 10^{-7}$ m/N.

The thermal increase of the piece being processed by the turning of the non-rigid shafts is pretty significant; that has merely direct influence on the values of extra axial forces. For the instance, thermal increase by 10° while shaft with means *1/d* = 5 is being operated, leads to 2000 N value of axial force, and the same one with means *1/d* = 25 leads to 9000 N already. So the present results claim verily the large values of extra constriction axial forces being possessed by thermal increase while processing. It is quite necessary to avoid their influence on processing accuracy by the certain method.

There have been experiments on lathe machine 1M63 performed for the dynamic estimation of the influence of constriction axial forces on rear center; among series of estimated regularities there was also the constriction forces influence on frequency response, or the Nyquist stability criterion. The force was provided by hydraulic drive under 1, 2, 3 MPa consistently. Empirically obtained (by method [2]) Nyquist stability criterions are represented in Fig. 4.

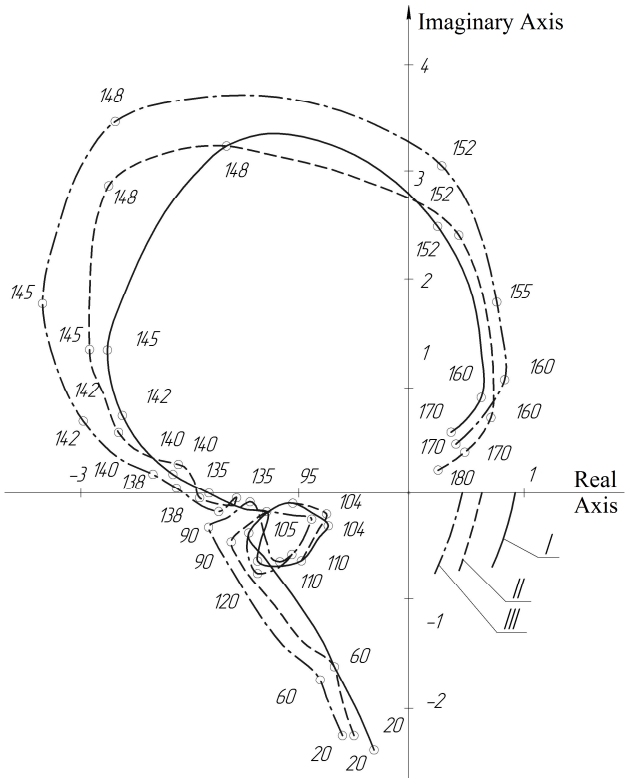

Fig. 4. Nyquist stability criterions obtained by the function of constriction axial forces under operating pressures of 1, 2, 3 MPa consistently.

During the Nyquist stability criterions values obtaining, the blank was clamped at three-jaw chuck with no SCR, was constricted by rotating center with 25 mm spindle constant overhang; the calibre and the size of part are 25 mm and 1450 mm consistently. Nyquist stability criterions obtained in blank center are represented in Fig. 4.

$$\alpha + \beta = \chi. \quad (1)$$

First, second, third ones of the time curve circuits were obtained while blank was being constructed by rear center under hydraulic cylinder pressures of 1 MPa, 2 MPa and 3 MPa consistently.

The examination of Nyquist stability criterions just allows one to know that the increase of blank constriction axial forces leads to the increase of vectors rays of the time curve circuits, especially in a close range to resonant frequencies (up to 1.1-1.2 times).

The axial forces increase predicts merely changes in range being nearly to resonant frequencies; phase shifts may reach 25-30°, other frequencies do 10°. The exploration of the dynamic rigidity ratio by the different axial forces at rear pole shows that the min of blank compliance depends on the blank constriction axial forces value. The theoretical and experimental research examination is supposed to claim verily need to control the blank constriction axial forces.

Thus, the force closure must be under control during the mechanical processing of non-rigid long-measuring shafts. The functional scheme of the Automatic Control System (by constriction axial forces) is represented in Fig. 5.

The shaft is clamped in the chuck, then constricted by rear dynamometrical point 2 with built-in dynamometrical center 3 one side of which is hanging back to blank, and the other one is to resilient element 4; its *X*-axis movement is under control of first primary transduce 5, the last one is clamped up rigidly to the dynamometrical rear center body relating to the resilient element 4 with a initial gap of *Δx*.

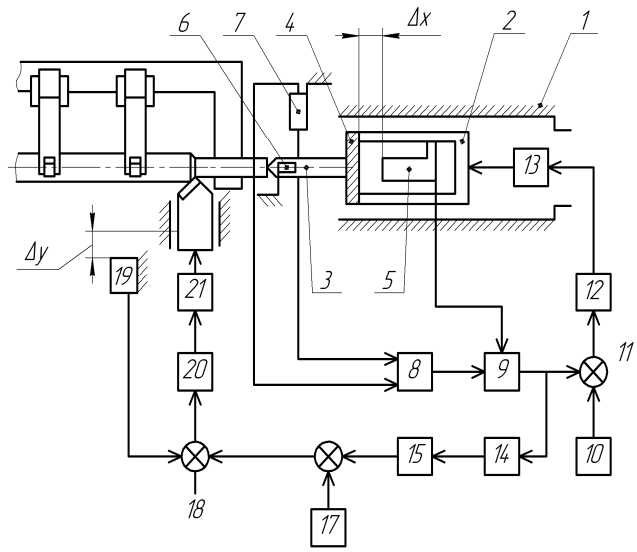

Fig. 5. The functional scheme of the ACS.

During the blank elongation (due to thermal expansion by the cutting), the dynamometrical center is moving by *X*-axis and deforming resilient element 4 (its deformation is tarred) which physical and mechanical properties claim axial stress of the blank while cutting. The deformation of the resilient element is detected by the first primary transduce 5.

The fundamental in the forming of the signal wanted for the confounding factors (caused by thermoforce-involving deformations of the revolving center in *YOZ* plane) reduction is performed in a way of static and dynamic components of the deformation detecting by primary transducers 6 and 7 consistently, and differential amplifier 8 by output signal applying of which, there is first scaler 9 transmission factor in the function of rear dynamometrical center 3 static and dynamic compliance bounded variation (in given coordinates) get varied. The *X*-axis thermal strain detected and transformed into electric signals are put by the first primary transduce 5 to first scaler 9, which performs the primary transduce 5 output signal valuation by the variation of transmission factor. In that way the first scaler 9 output signal related functionally to the blank axial thermal strain runs the blank constriction axial forces values in present range from axial forces controller 10; in other words, defined constriction axial force by rear center is being constant during all the processing (whether or not any geometric) influenced mechanical blank parameters and temperature ranges effects. The blank does not load by axial outer force of the thermal expansion additionally while elongating. The signals of controller 10 and cell 9 are compared at first fiducial cell 11; delta signal that is proportional to run signal proceeds to power amplifier 12, then to electrohydraulic actuator 13; it transfers dynamometrical rear center 3 related to the deadhead 1 in value proportional to blank deformation off the thermal expansion; due to that processing the blank constricted axial forces value supported by controller 10 stays constant.

At the same time the control function of the formed signal obtained as output from the first scaler 9 initiates the correlation of cutting depth value depending on the blank thermal strain in a way of action-changing to initial stress on controller 17 output, to cutting depth compensation drive through the consecutively united second scaler 14, cell "Dead Zone" 15 and second fiducial cell 16. Also, the control correcting signal value while performing machine is being set up proceeds with the second scaler 14 transmission factor variation; besides, the cell 8 dead zone value is supposed to be that kind to create its output control signal after the blank temperature while the processing increases by (15-20) °C as to ambient temperature only. Furthermore, the correction-control signal of the cutter tip depending on blank thermal expansion from the second fiducial cell 16 output enters the third fiducial cell 18 input where it is get compared with feedback signal by tip position from the fourth primary transduce 19 set on lathe support; then delta signal from fiducial cell 18 output enters the power amplifier 20 input; the output of last one is connected to the electrohydrostatic actuator 21 output.

The described conditions ensuring (including the deformations of deadhead power circuit axial and stabilization of the cutting depth correction) allows one to normalize the stress depth of surface layer strained state, to obtain pieces with the initial precision of the processing (incl. the influence of thermal strain from its compensation while turning).

IV. Results of experiment

The accuracy of the non-rigid shaft axial mode by the ACS applying was controlled after the processing of 400 mm length shafts at cross-sections 1, 2, 3, 4 (Fig. 6). The profile records of the axial sections were taken by the unit TAYLOR-HOBSON applying.

The blanks from structural steel of AISI 5135 with length 400 mm and diameter 25 mm were system-free processing and ACS processing consistently under the following cutting modes: rotation speed is 710 rpm, feed rate is 0.11 mm/rev; system-free processing - in two-pass way, cutting depths is 0.7 mm and 0.3 mm; ACS processing - in one-pass way, cutting depth is 1 mm.

The blank one-pass system-free processing is impossible due to arising autovibrations. The most significant cylindricity deviation values are represented by profile records in Fig. 6 (ACS processing). The error has been diminished in 2-3 times.

The profile records of the non-rigid shafts specific circumcision, system-free and ACS processing are represented in Fig. 7.

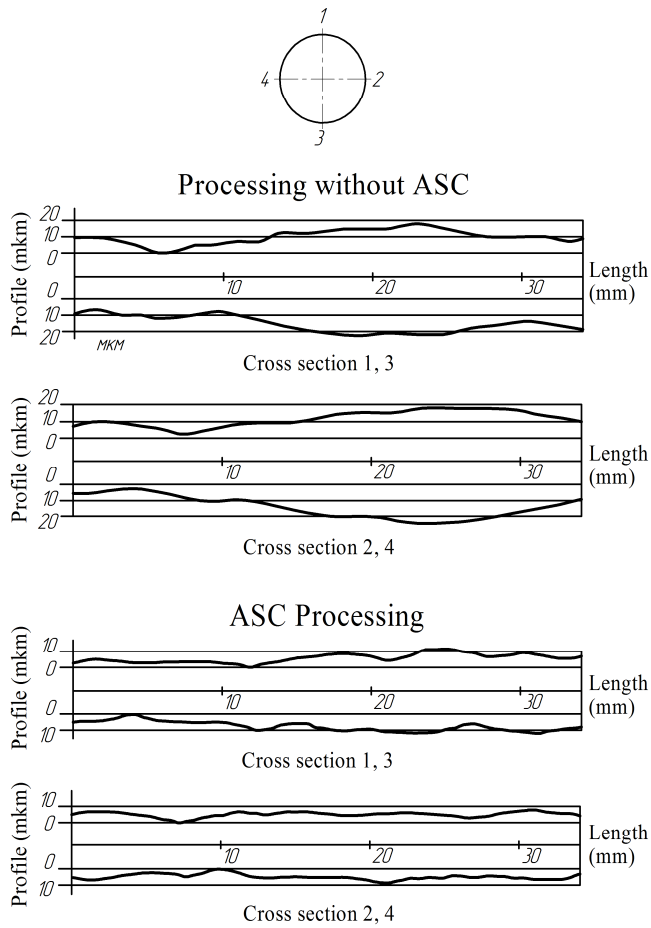

Fig. 6. The axial mode of the non-rigid shaft.

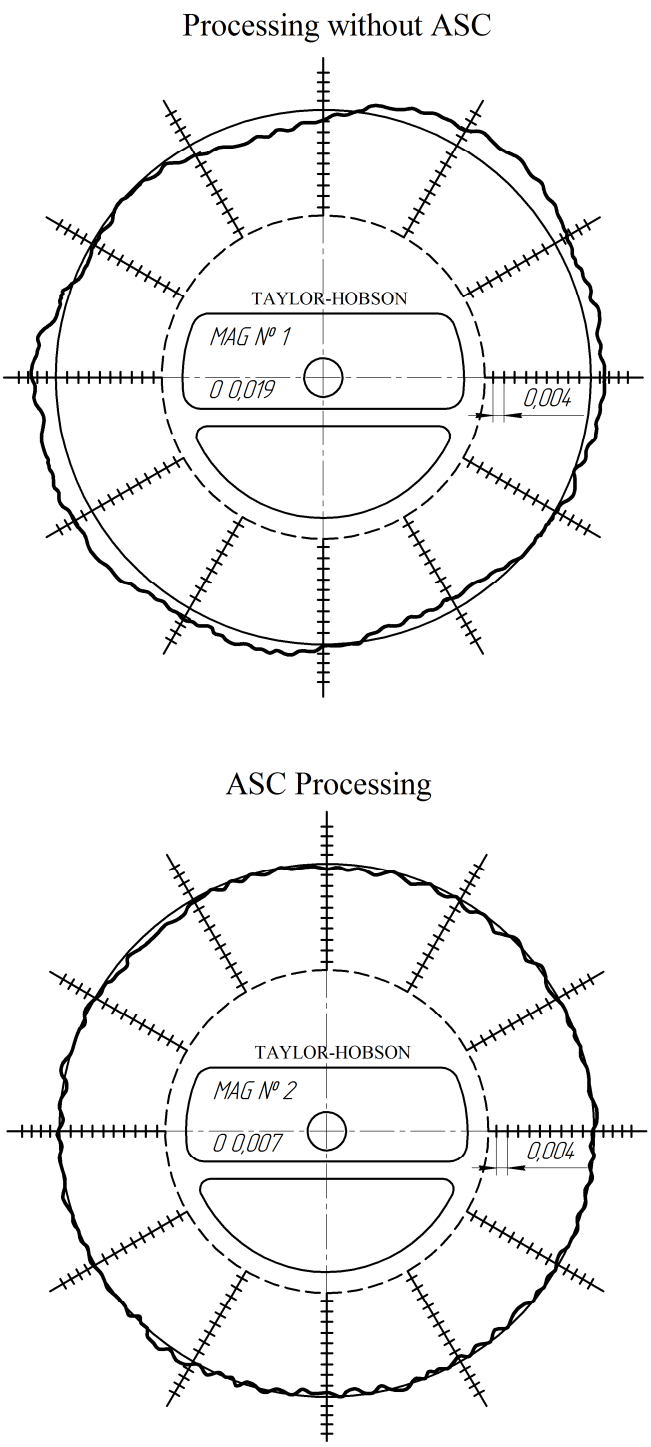

Fig. 7. The profile records of the non-rigid shaft circumcision.

Their examination has proved that the non-circularity deviation of the ACS processing shafts journals was diminished 2-4 times.

V. Conclusion

The applying of the proposing unit allows one to raise processing capacity 3-4 times, to gain roughness $Ra = 0.8$, to increase the cross-sectional accuracy up to 10-12 mkm/m in diameters and length ranges from 40 to 90 mm and from 2 to 4 m consistently; and, which is mostly important, to eliminate the residual deformation of a finished product.

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