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A METHOD FOR INCREASING ECONOMIC EFFECTIVENESS OF LOW RIGIDITY SHAFTS

The article presents a method for machining low rigidity shafts which allows improving their rigidity by the application of axial tensile force to a workpiece. To implement this new method, a special apparatus has been designed. The apparatus stabilizes elastic deformations in a workpiece and increases the machining accuracy allowing machine shafts apply superior parameters. As a consequence both effectiveness and profitability of the process are significant. The algorithm for evaluating effectiveness of machining process is also presented.

Keywords: *economic effectiveness; low rigidity shafts; machining accuracy.*

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МЕТОД ПІДВИЩЕННЯ ЕКОНОМІЧНОЇ ЕФЕКТИВНОСТІ ВИГОТОВЛЕННЯ ВАЛІВ МАЛОЇ ЖОРСТКОСТІ

У статті представлено метод механічної обробки валів малої жорсткості, який дозволяє збільшити їх жорсткість у процесі обробки, для цього застосовується осьове зусилля натягу. Представлено розроблений пристрій, який стабілізує еластичні деформації, а також підвищує точність обробки валів малої жорсткості. Обробка валів при використанні пристрою дозволяє застосовувати більш високі параметри й у результаті – значне збільшення рентабельності їх виробництва. Наведено також алгоритм визначення економічної ефективності обробки валів за запропонованим методом.

Ключові слова: *економічна ефективність виробництва; вали малої жорсткості; точність обробки.*

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МЕТОД ПОВЫШЕНИЯ ЭКОНОМИЧЕСКОЙ ЭФФЕКТИВНОСТИ ИЗГОТОВЛЕНИЯ ВАЛОВ МАЛОЙ ЖЕСТКОСТИ

В статье представлен метод механической обработки валов малой жесткости, позволяющий увеличить их жесткость во время обработки путем приложения к детали осевой растягивающей силы. Представлена спроектированная установка, стабилизирующая эластичные деформации детали, а также позволяющая увеличить точность обработки валов малой жесткости. Обработка валов с применением установки дает возможность применения более высоких режимов и в итоге – значительно повысить эффективность их изготовления. Показан также алгоритм определения эффективности обработки валов по предложенной методике.

Ключевые слова: *экономическая эффективность; валы малой жесткости; точность обработки.*

Introduction. Rotating parts such as shafts, discs, sleeves or cylinders constitute approximately half of all machine parts. Low rigidity shafts make up to 12% of all industrially used parts. These shafts can be applied in aircraft industry (e.g., spring shafts, elastic shafts, torque shafts, suspension springs, screws), machine-tool industry (e.g., various devices, mechanisms, precision and special tools, drills, reamers,

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screw taps, boring bars), machine-building industry (e.g., shafts, turbine and pump rotors, guide screws), in agricultural machinery (e.g., axle-shafts of tractors and harvesters) or automotive industry (Arnaud et al., 2011; Urbicain et al., 2012; Swic et al., 2012).

A low rigidity shaft is a shaft which length-to-diameter ratio is not lower than 10. Due to specific nature of machining of low rigidity shafts, it is difficult to produce these parts with the required accuracy regarding their shape, dimensions, and surface quality (Li et al., 2003; Xiong et al., 2003; Swic et al., 2011; Qi et al., 2013; Lopes et al., 2013). Their low inherent rigidity along with relatively low – compared to rigid assemblies of a machine tool – rigidity of shafts may lead under specific conditions to vibrations. Machining process can be interrupted and destabilized by numerous factors (e.g., high eigen deformations of parts, tool and apparatus work, chips, dust), which results in lower machining accuracy of low rigidity shafts (Campa et al., 2008; Huang et al., 2009; Swic et al., 2013). Conventional methods for achieving accurate machining of low rigidity shafts are based on multi-pass machining, lowered machining parameters, the use of steadies as well as the application of additional treatments and manual lapping. With these methods, process efficiency may be considerably decreased; in many cases the required accuracy may not be achieved at all (Jianliang et al., 2006; Gola et al., 2009). Also, these methods are incompatible with current requirements for automation; moreover, they are economically ineffective and inefficient.

Machining accuracy of low rigidity shafts depends on numerous factors (Ratchev et al., 2004; Cardi et al., 2008; Halas et al., Swic et al., 2013). Factors decreasing machining accuracy of low rigidity elastic-deformable shafts include: unsuitable fixing of parts, displacements of part alignment axis, inaccurate alignment of parts, shape of clamping elements, elastic and plastic deformations. In this connection it should be mentioned that reliable fixing in machining of low rigidity shafts should prevent reciprocal shifting of aligned surfaces of parts and grips; also, such fixing should prevent the workpiece from being pulled out from the grip jaws (Swic et al., 2014).

Machining accuracy of low rigidity shafts can be increased by controlling the accuracy of forming them at elastic-deformable state via the application of axial tensile force.

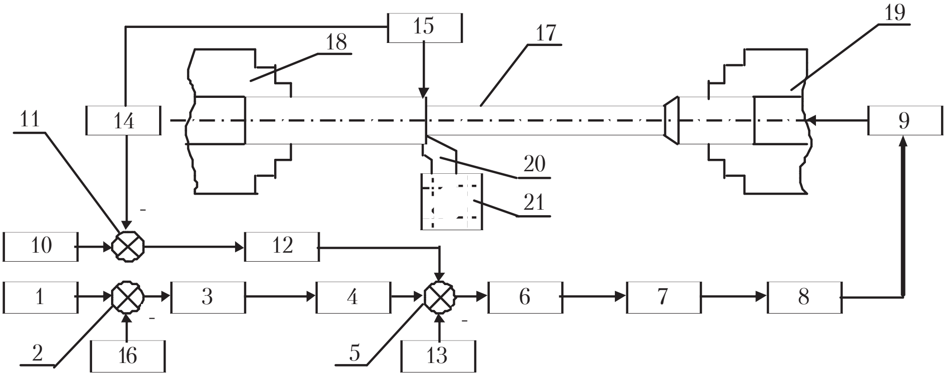
Apparatus for the machining of low rigidity shafts. Based on the results of the conducted theoretical and experimental investigations, a method for mechanical machining has been developed. This method allows attaining the required accuracy in turning and, at the same time, controlling the elastic-deformable state of shafts.

The machining of low rigidity shafts is accompanied by random disturbances leading to vibrations; the work in the resonant zone leads, in turn, to higher roughness of part surface, life of tool's cutting edge decreases, the geometry of the layer being cut changes, which leads to higher elastic deformations in the technological system (TS, i.e. MCWT = machine – grip – workpiece – tool) and lower machining accuracy.

In the machining of low rigidity shafts, based on the calculated elastic deformations of parts, values of the voltage applied on the input of a direct current engine are varied, while adequate angular and linear displacements are made on the engine's output, these displacements are then converted by the tension mechanism into the axial tensile force that is applied to the shaft with low rigidity.

Prior to machining, a certain initial tensile force should be generated. For this, any clearance in the tension mechanism must be removed so that real and determined values of the tensile force be equal; once the machining process is started, real and determined values of elastic deformations of parts must be equal, too.

The block diagram of the apparatus for the new machining method for low rigidity shafts is presented in Figure 1. The apparatus consists of: velocity selector 1, first comparison element 2, velocity controller 3, initial tensile force selector 4, comparison element 5, tensile force controller 6, controllable transducer 7, direct current engine 8, tensioning mechanism 9, as well as elastic deformations selector 10, second comparison element 11, nonlinear controller of elastic deformations 12, tensile force sensor 13, block of absolute value determination 14, elastic deformations sensor 15, velocity sensor 16.



Note: 1 – velocity selector, 2 – first comparison element, 3 – velocity controller, 4 – selector of initial tensile load, 5 – comparison element, 6 – tensile force controller, 7 – controllable transducer, 8 – electromotion device, 9 – tensile force application mechanism, 10 – controller of elastic deformations, 11 – second comparison element, 12 – nonlinear controller of elastic deformations, 13 – tensile force sensor, 14 – block of module determination, 15 – elastic deformations sensor, 16 – velocity sensor, 17 – workpiece, 18 – grip I of shaft end, 19 – grip II of shaft end, 20 – cutting edge, 21 – tool post.

Figure 1. **The apparatus used in the machining of low rigidity shafts**
(Swic et al., 2011)

The inputs of the comparison element 5 are additionally connected to the tensile force sensor 13 and to the output of the nonlinear controller of elastic deformations 12, whose input is connected via the second comparison element 11 to the elastic deformations controller 10. The sensor 1 of the elastic deformations 5 is connected via the block of absolute value determination 14 to the second input of the comparison element 11, while the velocity sensor 16 is connected to the second input of the first comparison element 2. One end of the workpiece 17 is mounted in the grip 18, while the other is in grip 19 connected to the tensioning mechanism 9. The machining of this part is made using the tool 20 fixed in the tool post 21.

The apparatus is operated under conditions required for generating initial tensile force. At the start, the voltage values on the outputs of the elastic deformations sensor 15 – U_{15}, of the velocity sensor 16 – U_{16} and of the tensile force sensor 13 – U_{13} are equal to zero. The voltage U_{12} on the output of the nonlinear controller of elastic deformations 12 is also equal to zero. The input of the velocity controller 3 is supplied through the first comparison element 2, with the voltage U_1 from the velocity selector 1 — the velocity controller 3 is in saturated condition: the output voltage (the saturation voltage of the velocity controller 3) passes through the initial tensile force selector 4, comparison element 5, tensile force controller 6, controllable transducer 7 and direct current engine 8 to the tensioning mechanism 9. There is a rapid increase in the velocity of the engine 8 and of the tensioning mechanism 9. With the velocity increase, the voltage U_{16} of the velocity sensor 16 increases, too, while the voltage U_2 on the output of the first comparison element 2 equal to:

$$U_2 = U_1 - U_{16}, \tag{1}$$

decreases. When the velocity approaches the required value (of velocity selector 1), the voltage U2 on the output of the first comparison element 2 corresponding to (4) tends to zero. The velocity controller 3 leaves the saturation state and the value of stabilization velocity is determined. Lost motion of the tensioning mechanism 9 has a determined velocity, which prevents undesired changes.

When the lost motion is determined, the initial tensile force in the mechanism 9 stabilizes, its value is proportionate to the output voltage U_4 of the initial tensile force selector 4. This stage has the following course: the voltage on the output of the elastic deformations sensor 15 and the voltage U_{12} on the output of the nonlinear controller of elastic deformations 12 remain equal to zero. On selection of the lost motion, the voltage U_{13} is generated on the output of the tensile force sensor 13, while the voltage on the output of the comparison element 5:

$$U_5 = U_4 + U_{12} - U_{13}, \tag{2}$$

begins to decrease. The voltage supplied by the controllable transducer 7 to the engine 8 is decreased, leading to a decrease in the engine velocity. When the transitory process is over, the velocity of the engine 8 decreases to zero, while the velocity controller 3 enters the saturation state again. The voltage U_4 on the output of the initial tensile force selector 4 remains constant and determines the value of initial ensile force. Once the initial tensile force has been generated, the machine feed is switched on and the machining process for shafts begins. At this stage, the device operates in the stability mode in order to maintain the required value of elastic deformations. The U_{15} voltage from the elastic deformations sensor 15 is supplied through the absolute value block 14 to the second comparison element 11, where it is compared with the U_{10} voltage of the elastic deformations controller 10. The absolute value block 14 converts the U_{15} voltage of the elastic deformations sensor 15 into constant mark voltage U_{14}. If the correct value of elastic deformations is lower than the required one (the value of elastic deformations may, in special cases, be equal to zero), then the voltage on the output of the second comparison element 11:

$$U_{11} = U_{10} - U_{14}, \tag{3}$$

is greater than zero, while the output voltage U_{12} of the non-linear controller of elastic deformations 12, due to the non-linearity of its characteristics, is equal to zero. This apparatus maintains the set value of the initial tensile force.

If elastic deformations exceed the set point value, then in Equation (6) the mark of voltage U_{11} changes on the output of the second comparison element 11 and voltage U_{12} appears on the output of the non-linear controller of elastic deformations 12. At the same time, in accordance with (5), the voltage U_5 increases, which leads to an increase in the engine 8 and in the tensile force of the shaft. As a result, elastic deformations of parts decrease to the required level. The introduction of the element for determining the absolute value 14 (constant-mark voltage) causes that the apparatus, in compliance with the described algorithm, increases the value of the tensile force, while the absolute value of elastic deformations increases irrespectively of the mark of these deformations. This allows for compensating for elastic deformations, both when the equivalent cutting force makes the part shift towards the cutting edge and when the part is pulled off (pushed away from) this cutting edge.

Machining accuracy of low rigidity shafts can be increased by stabilizing elastic deformations via the application of the tensile force to the part. High accuracy of stabilization of elastic deformations of the part in steady and transient states allows increasing the machining accuracy of shafts with low rigidity.

Evaluation of machining process effectiveness. To evaluate the effectiveness of machining process and its individual operations, prime cost is often taken into consideration. The evaluation of different variants of production is made in accordance with technological prime costs (excluding the cost of materials, as they are the same for the variants being compared). However, when the compared variants differ with regard to the amount of materials used, full prime costs of parts should be analyzed (Ouyang et al., 2007; Gola et al., 2011, Swic et al., 2013).

The effectiveness parameters of the technological process can be expressed as expenditure:

$$P_N = E_N K + C_P G, \tag{4}$$

where E_N is the standard coefficient of capital expenditure refund; K denotes the capital expenditure (initial expenditure); C_P is the full prime costs of parts; G is the annual production of parts.

The total prime cost of the part:

$$C_P = C_1 + C_2, \tag{5}$$

where C_1, C_2 are parts of the full prime cost, dependent on cutting parameters and material consumption.

Hence:

$$P_N = E_N K + (C_1 + C_2)G. \tag{6}$$

This criterion can be applied to examine two types of optimization: optimization of variants and that of parameters.

The optimization of variants consists in selecting the optimum one within the machining process, because the required part quality for the assumed process efficiency can be obtained by various machining methods that differ with regard to devices, instrumentation, tooling and workpiece used.

In a general case, this technological problem can be solved in j-th ways, while for the j-th variant ($j = 1, \ldots, J$) the expenditure can be determined using the dependence:

$$P_{Nj} = E_N K + (C_{1j} + C_{2j})G. \tag{7}$$

The parameters E_N and G generally do not depend on j (E_N is selected in accordance with industrial standards; G is selected in compliance with the plan); still, it must be observed that more efficient variants allow runing the production using fewer machines and devices. The aim of variant optimization is to select the one with the lowest possible P_N, i.e. min P_{Nj} at $I \le j \le J$.

Capital expenditure depends on the technological means applied for the j-th variant. Some part of the prime costs C_{2j} depends on the workpiece used, auxiliary materials for every variant of multi-pass machining or elastic-deformable machining for different patterns of alignment. For this reason, it cannot be determined in an unequivocal way, which gives rise to the problem of variant optimization. The technological part of the prime costs C_{1j} mainly depends on machining parameters (v, a_p, f), inter-operation allowances, dimensional tolerance and life of the cutting tool (parametric optimization). Parametric optimization consists in selecting rational technological parameters for a given machining method. Let $\overrightarrow{Y_j}$ be the vector the components of which are the parameters and $\overrightarrow{X_j}$ be the vector the components of which are the technological parameters in the j-th variant. Also, we take into consideration the limitations denoting closed sets which include both the vector of technological parameters and the vector of alignment parameters:

$$\overline{Y_j} \in N_{oj},\ \overline{X_j} \in M_{oj}, \tag{8}$$

where N_{oj}, M_{oj} denote respectively the closed set of acceptable values of the vector $\overrightarrow{Y_j}$, $\overrightarrow{X_j}$. Hence, for the optimization of variants and parameters, the following condition should be met:

$$\min_j PN_j(\overline{Y_j} \in N_{oj}; \overline{X_j} \in M_{oj}); \tag{9}$$

$$\min_{1\le j\le J}\left[E_N K_j + G\cdot \min_{\overline{Y_j}\in M_{oj}} C_{2j}(\overline{Y_j}) + G\cdot \min_{\overline{X}_j\in M_{oj}} C_{1j}(\overline{X}_j)\right]. \tag{10}$$

Here, we consider the full prime cost C_P of manufacturing the part, so the mathematical expression aimed at both parametric and variant optimization can be written as:

$$\min_{1\le j\le J}\left[\min_{\overline{Y}_j\in N_{oj}} C_{2j}(\overline{Y}_j) + \min_{\overline{X}_j\in M_{oj}} C_{1j}(\overline{X}_j)\right], \tag{11}$$

while for the optimization of variants when selecting the most suitable pattern of alignment in the machining of elastic-deformable shafts with low rigidity:

$$\min_{1\le j\le J}\left[\min_{\overline{Y}_j\in N_{oj}} C_{2j}\left|\overline{Y}_j\right|\right]. \tag{12}$$

The algorithm in Figure 2 was applied to obtain solutions for the problem and to perform all indirect computations for parameters and prime costs to obtain the most suitable variant of alignment and fixing in the machining of an elastic-deformable shaft. Some of the blocks (2 through 18) allow entering input data to compute technological parameters of machining, dimensions of clamping elements, and values of contact deformations. Other blocks (19 through 30) do the calculations and compare the full prime cost C_{Pj} for the j-th variant of alignment and the variant determined in the analysis of the previous j – 1 variants.

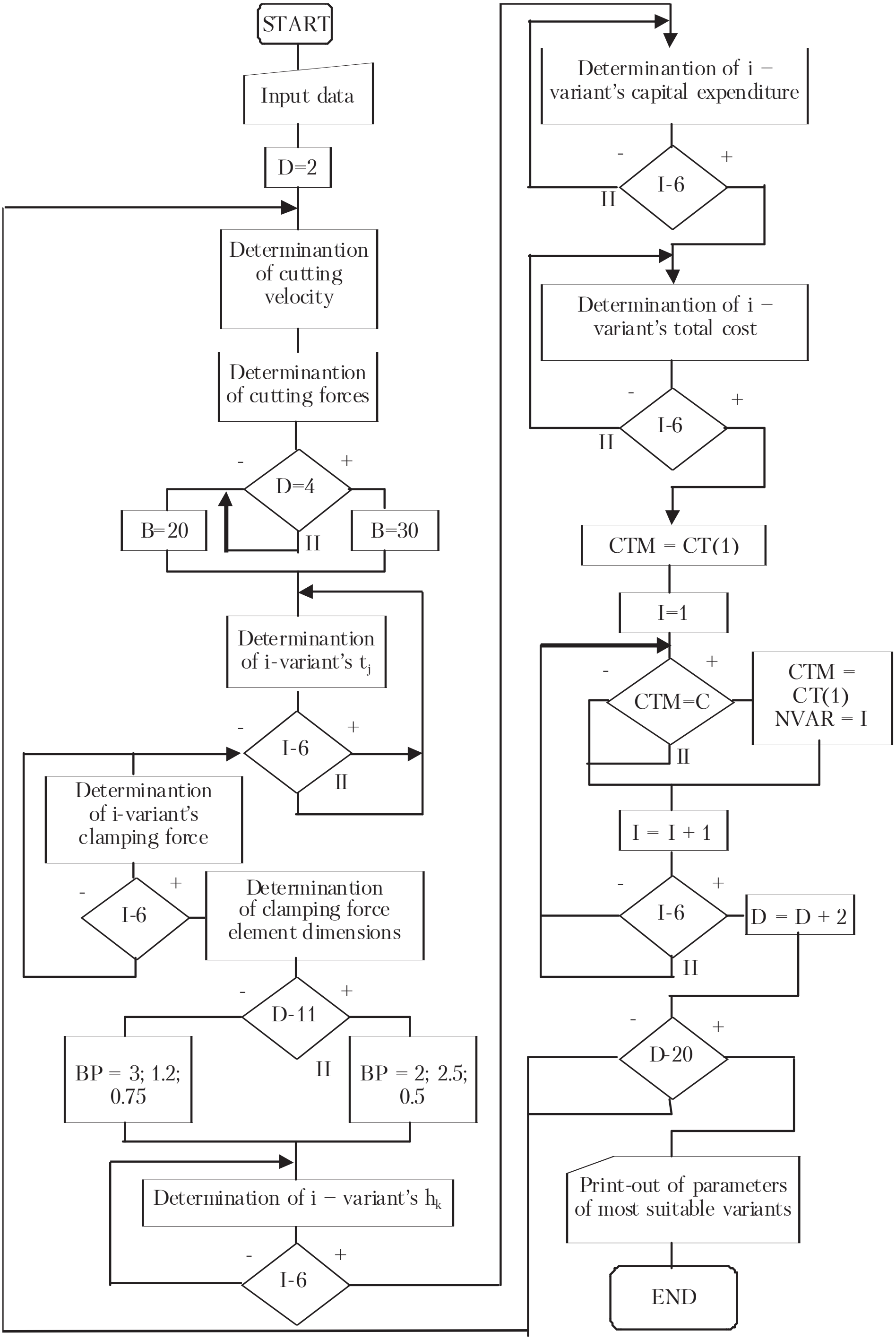


Figure 2. **Block diagram for determining parameters and costs in tensile machining of an elastic-deformable shaft**

When calculating the initial time (variant 1) such analysis was not performed. Variant 2 was compared with variant 1; variant 3 was then compared with the best of the previous two variants. Following the calculation of the prime costs for all the 6 variants, technological parameters of the best one are determined in accordance with the prime cost criterion.

Conclusions. The paper presents a new method of low rigidity shafts machining process. This method allows increasing the effectiveness of machining. To apply this new method, a special apparatus has been designed. The apparatus allowed increasing shaft rigidity due to the application of tensile force during machining; also, this device ensured high stability of elastic deformations of parts in both steady and transient states as well as higher accuracy of low rigidity shafts. The factors that decrease machining accuracy of low rigidity elastic-deformable shafts include: unsuitable fixing of parts, displacements of the part alignment axis, inaccurate alignment of parts, shape of clamping elements, elastic and plastic deformations. Moreover, the algorithm and computer software for determining parameters and own cost of machining process when machine low rigidity elastic-deformable shafts was developed. Conducted calculations proved the economic effectiveness of the developed method of machining low rigidity elastic-deformable shafts.

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