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LATHE TURNING MODE OPTIMISATION FOR PARTS WORKING UNDER CONDITIONS OF CYCLIC LOADING

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Abstract. This work is devoted to questions of technological cyclic durability maintenance, of the material for parts working under cyclic loading conditions, by lathe processing optimization. The analysis of the impact of the surface layer quality on fatigue characteristics is described for parts operating under cyclic loads. Survey of methods for evaluating cyclic durability is completed, which showed lack of information about the mathematical relation between the cyclic durability of the part's material and technological conditions of its production. A fatigue experimental study was carried out, the results of which allowed to create a mathematical model of cyclic durability of the material from lathe processing mode and tension cycle. The complex objective function that takes into account the dependence of cyclic durability of turning from technological conditions of handling and processing was developed. It is proposed to determine tension cycle for the most unsafe parts of a constructive element with consideration of conditions of service using the finite element method. The mathematical model of lathe processing of parts working under conditions of variable cyclic loads is developed and represented by total complex target function and system of constraints, including set of constrains on: feed, speed, strength and power of cutting, cutting precision, tool life and roughness of the workpiece. In addition, this mathematical model takes into account the actual characteristics of the material and expands its use to other materials of alloyed chromium steel. Submitted multi-criteria task is solved by using the method of sliding clearance. Steel 40X GOST 4543-71 was used as an example for the proposed mathematical model of the part turning process, part operates under cyclic loading, and best values for feed and cutting speed are calculated.

Keywords: cyclic loading, lathe processing, technological conditions, fatigue, handling, tension.

Introduction

Fatigue is the cause of the failure of more than 70 % of machine parts such as shafts, gearwheels, connecting rods, pins, gears, rotors and their attachments, working under variable loads. Research [1–8] proved that the robustness of the technical tools largely depends on the conditions of surface layer of the part's material, especially those working under conditions of variable loads. In addition, the number of cycles to the destruction of parts essentially depends on the conditions of use – peak cycle stress.

Formation of the surface layer mostly defined by cutting machining, accompanied by plastic deformation, heating and structural changes of the part's material. Thus, the surface layer is formed with specific mathematical sign and value of residual stresses, depth and degree of consolidation, as well as surface roughness, the value of which significantly affects the fatigue properties of the material [9–11].

Problem definition

Technological modes of part production are assigned according to the engineer's regulations of exact size, quality parameters and, if necessary, the hardness of the surface layer. This limits the technological assurance of fatigue characteristics of the part's material and prediction on cyclic durability of parts in operational activities. In addition, due to the constant increase in the speed of upgrading and improving of machines and mechanisms it is necessary to ensure maximum performance of parts processing, taking into account the requirements for their quality and operational purposes.

Objectives of research and task statement

The aim of this work is technological provision of maximum values of cyclic durability for parts material and efficiency of its manufacture by determining optimal modes of lathe turning.

To achieve this, next tasks were set:

– carry out analysis of surface layer quality impact on resistance to fatigue;

– conduct experimental research on fatigue to determine the relation of cyclic durability and technological conditions of machining;

– define mathematical dependence of cyclic durability from lathe turning modes and operational loads;

– develop a comprehensive target function, which consists of two partial optimization criteria: cyclic durability and lathe process productivity based on actual characteristics of the parts material and set of constraints;

– solve the multi-criteria optimization task.

Analysis of current information sources on the subject

Mechanical treatment of parts causes plastic deformation, heating and structural changes in the surface layer of the material and is accompanied by uneven in depth and values deformations and residual stresses [9–11]. Depending on dominant phenomenon (plastic deformation, heating or structural changes), the surface layer can have different physical and mechanical characteristics as well as structure-phase composition [2, 3].

Fatigue strength and cyclic durability of parts, working under conditions of variable cyclic loading, depends on surface roughness, individual defects and irregularities that contribute to stress concentrations that may exceed the ultimate tensile strength [2–4]. In source [3], the relations of operating properties of parts and their connections with the quality parameters of the surface layer are described, and the degree of influence of each of these parameters is illustrated. According to this data, the biggest impact on the fatigue strength of roughness parameters are R_{max} and S_m parameters. Moreover increasing of R_{max} value will reduce fatigue strength significantly, while increasing of S_m value – significantly increases fatigue strength.

In [2, 5–7] authors found that the fatigue strength of machine parts depends not only on peak to trough height, but also, to a large extent, on the degree of hardening and residual stress of the surface layer. Researchers in [2, 5, 6] found that the presence of compressive residual stress in the surface layer increases fatigue strength, and the presence of residual tensile stress – reduces fatigue strength.

Results of studies [7] show that the defamation of the surface layer of the metal parts formed by turning and polishing, increases fatigue limit by 20–25 % due to slander, and can be increased by another 12–15 % by reducing the height of the roughness during the transition from turning to polishing.

Structural changes in the metal during mechanical processing, in particular “burns” of polished surfaces, are a major reason for the parts durability decline. Tensile residual stresses are usually developed in the areas of relieved metal, and reduce the fatigue strength. On borders of restructured areas cracks are often developed, that become concentration of fatigue destruction [8].

According to GOST 25.504-82 cyclic durability is determined by dependency that takes into account only the value of ultimate tensile strength of the material $\sigma_{\square}$ and part roughness R_Z.

Damage accumulating models and hypotheses of fatigue damage are commonly used in calculating the strength during variable loads, the most famous is the Palmgren-Miner hypothesis of linear damage accumulation, however, a number of experimental studies have not confirmed this hypothesis [12].

There are also non-linear damage accumulation hypothesis, which take into account the level of load, mutual loadings, stages of the process of damage accumulation [12, 13]. However, examined hypotheses and models do not take into account the characteristics of the surface layer, other than $K_{F\sigma}$ coefficient (in GOST 25.504-82), and cannot be used for technological provision of maximum values of cyclic durability of dpart’s material, as well as determination of the optimal mode for machining.

Prediction of cyclic durability in [14] is performed on the basis of surface roughness, hardness changes and residual stress in the depth of the surface layer. However, it is not considered that the destruction of parts under variable loads usually happens at the expense of fatigue cracks on the surface in a stress concentrations.

In [15] it is stated that a key element in the manufacture of parts that work under variable loads is final machining. But choosing the best method and modes of machining is based under consideration of a limited number of surface layer quality parameters. In particular, the impact of residual stresses that significantly affect the cyclic durability is not considered.

Thus, research of the surface layer quality impact on the characteristics of part's fatigue strength and lack of information about the mathematical relations between the cyclic durability of the material and technological conditions of production, suggest the relevance of technological provision of maximum values of cyclic durability for part's material and efficiency of its manufacture by determining optimal modes of lathe turning.

Analysis of current information sources on the subject

The influence of technological conditions of machining on fatigue properties of part's material was studied on samples of structural steel 40X GOST 4543-71.

For carrying out experimental studies of fatigue, according to GOST 25.502-79, samples were prepared according to the scheme – clean bend during rotation of the part (Fig. 1). Moreover, to remove scratches on the surface of the sample and round sharp edges on samples additional mechanical grinding and polishing was performed. For nobility defamation from the previous machining, samples were subjected to thermal cultivation in protective gas environment in next conditions: heating to a temperature 450 ºC, endurance for 2 hours, cooling in the furnace.

Fig. 1. *Exterior of sample for fatigue testing*

Lathe turning process was performed in lathe center HAAS ST20 with cutter PVVNN 2525M-16Q and cutting plate from cubic boron nitride VBGW 160404T00815SE without cooling.

Machining of samples from each of the three groups was performed with a depth of cut t = 0.3 mm and the cutting speed V = 80 m/min and feed S = 0.12 mm/rev for the first group, V = 120 m/min; S = 0.12 mm/rev for the second and V = 180 m/min; S = 0.08 mm/rev for the third group.

Tests were conducted on fatigue testing machine МУИ -6000 at a frequency of 2000 rev/min.

Fatigue hacking sample shown in Fig. 2, where 4 main areas can be singled out by difference in microstructure: area of origin of fatigue damage (1); area of progressive cracks development (2); area of accelerated cracks development (3); fracture area (4), which is typical of fatigue.

Values of the actual stress cycle and number of cycles to fracture, obtained during experiment, allowed to apply methods of regression analysis [16], to establish mathematical dependence of cyclic durability from lathe processing modes and cycle tension, with confidence probability of F = 0.95 (Fisher's criterion):

$$N(S,V,\sigma)=e^{\left(14.437+0.0048V+13.006S-13.19\sigma+0.002VS-0.002V\sigma-5.941S\sigma+0.0000004V^2+2.929S^2+3.013\sigma^2\right)}, \quad (1)$$

where *S* is tool submission for one turn of the spindle, mm/rev; *V* is cutting speed, m/min; σ is stress cycle, MPa.

Fig. 3–5 depict the experimental and calculated values of cyclic durability of samples depending on stress cycle for the different groups of lathe processing modes used on samples of structural steel 40X GOST 4543-71.

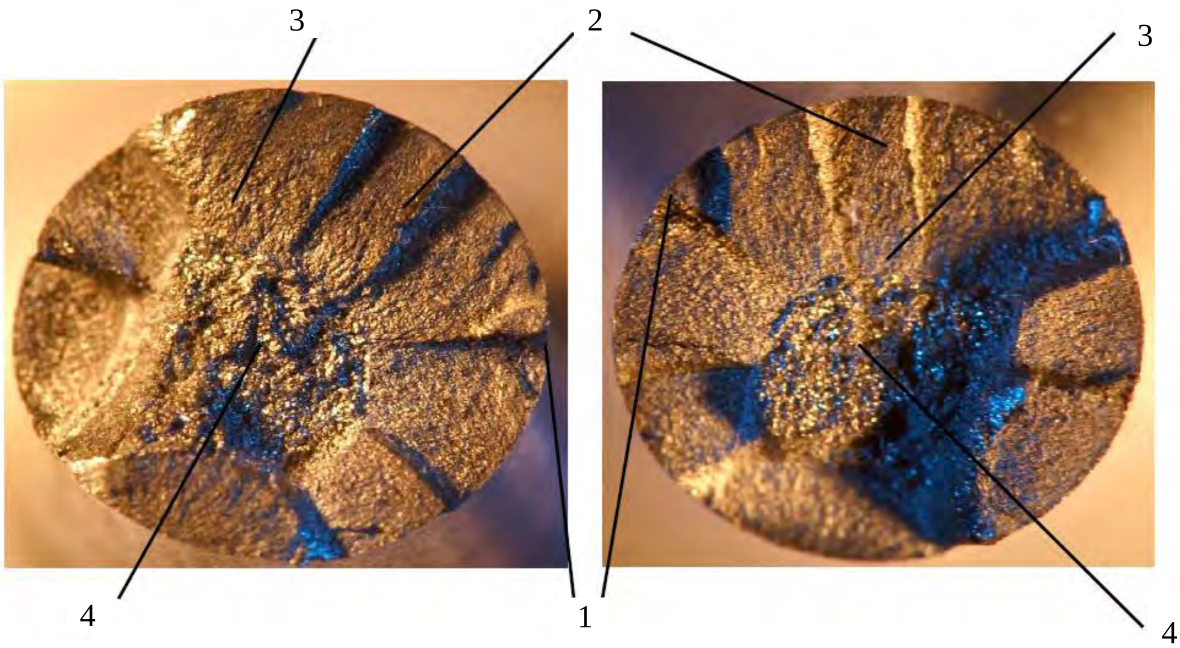

Fig. 2. *Fatigue hacking sample*

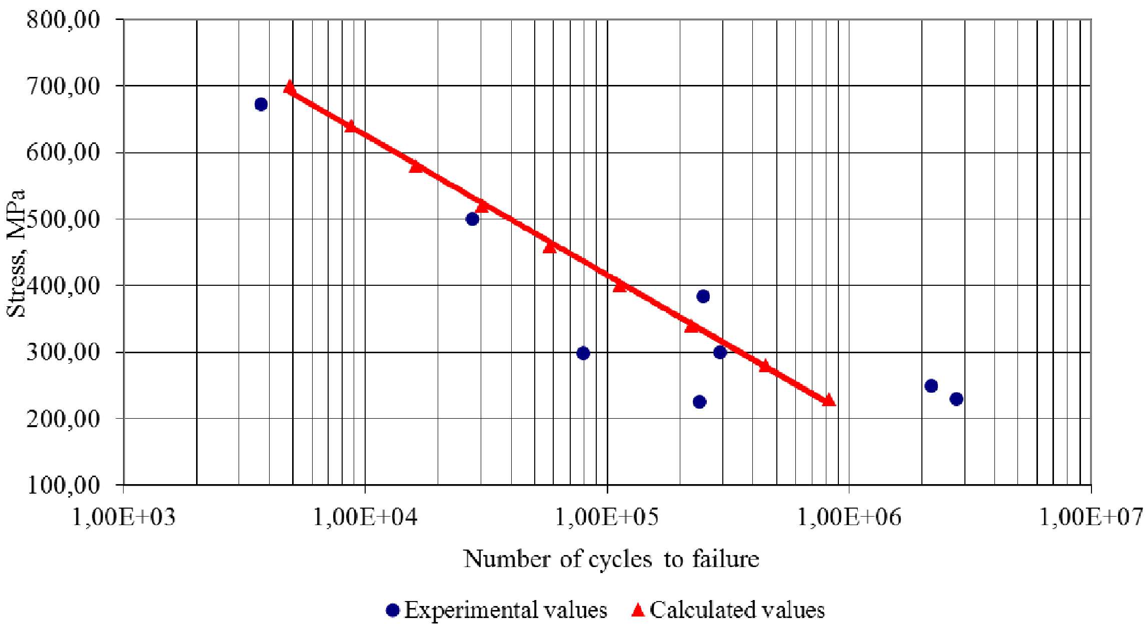

Fig. 3. *Calculated and experimental values of cyclic durability of samples with structural steel 40X GOST 4543-71 with V = 120 m/min; f = 0.12 mm/rev; t = 0.3 mm*

Fig. 6 graphically presents the dependence of cyclic durability of samples from stress cycle and processing modes. Increasing the supply from 0.08 mm/rev to 0.12 mm/rev significantly increases cyclic durability compared with an increase of cutting speed from 80 m/min to 180 m/min. The highest values of cyclic durability obtained in processing with cutting speed of 120 m/min and feed 0.12 mm/rev.

The dependence of cyclic durability from machining modes and stress cycle (1) can form a complex objective function [17], which consists of two partial optimization criteria: cyclic durability and processing performance of machining.

$$C(S,V,\sigma)=\left(\alpha_1\cdot\left(\frac{N(S,V,\sigma)-N_{\min}}{N_{\max}-N_{\min}}\right)+\alpha_2\cdot\left(\frac{\Pi(S,V)-\Pi_{\min}}{\Pi_{\max}-\Pi_{\min}}\right)\right),\qquad(2)$$

where α_i, i = 1, 2 are factors that determine the importance of each partial criterion, the value of which is estimated by experts; N is finish machining performance, 1/min; S is submission of tool for one turn of the spindle, mm/rev; V is cutting speed, m/min; σ is stress cycle, MPa.

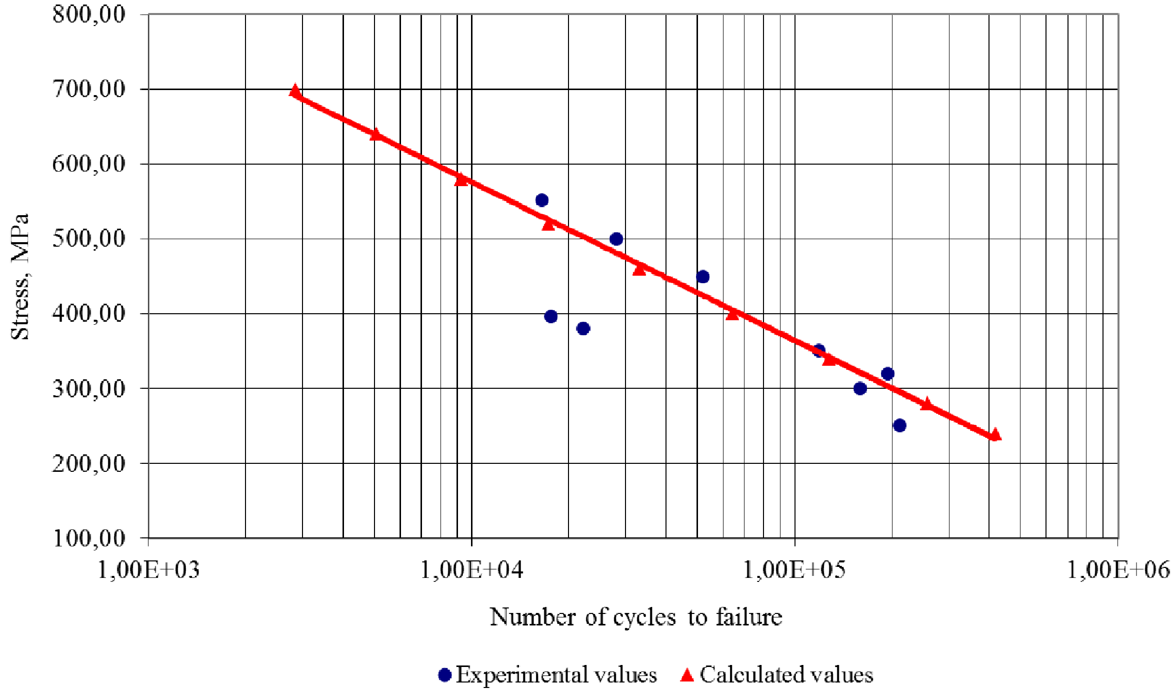

Fig. 4. *Calculated and experimental values of cyclic durability of samples with structural steel 40X GOST 4543-71 with V = 80 m/min; S = 0.08 mm/rev; t = 0.3 mm*

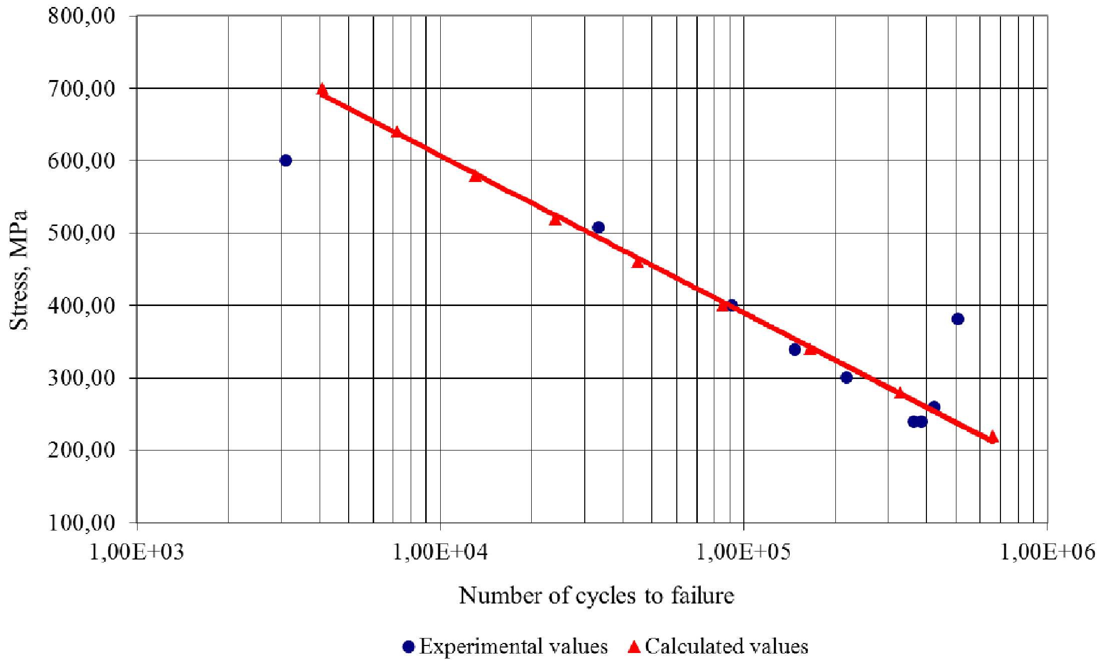

Fig. 5. *Calculated and experimental values of cyclic durability of samples with structural steel 40X GOST 4543-71 with V = 180 m/min; S = 0.08 mm/rev; t = 0.3 mm*

Tension cycle for the most unsafe constructive element of the part, with consideration of operating conditions, can be calculated by using the finite element method [18].

Finish machining productivity is represented as:

$$\Pi = \frac{1000VSt}{\pi DLh}, \tag{3}$$

where *t* is cutting depth, mm; *D* is diameter of the workpiece, mm; *L* is estimated length of treatment, i.e. the total length of the passage of the tool in the direction of feed, mm; *h* is allowance value, mm.

Thus, the mathematical model of lathe processing of parts, working under conditions of variable cyclic loads, is represented as a sum of objective function and system of constraints (by: feed, speed, strength and power of cutting, cutting precision, tool life and surface roughness):

$$C(S,V,\sigma) \Rightarrow \max, \quad as \begin{cases} S \ge S_{\min}; \quad S \le S_{\max}; \\ V \ge \dfrac{\pi D_0 n_{\min}}{1000}; \\ V \le \dfrac{\pi D_0 n_{\max}}{1000}; \\ P_{\max\ o.з.} \ge P_x = 10 C_{Px} t^{x_{Px}} s^{y_{Px}} v^{n_{Px}} K_{Px}; \\ N_{\partial в}\eta \ge \dfrac{10 C_{Pz} t^{x_{Pz}} s^{y_{Pz}} v^{nPz} K_{Pz}}{1020 \cdot 60}; \\ 0,5 \cdot TD \ge \begin{pmatrix} (W_{\max} P_{\max} - W_{\min} P_{\min}) + \Delta\varepsilon_y + \\ +\Delta_н + \left(\dfrac{\pi D l_\partial N}{1000 s} + L_н \right) \cdot u_0 \Big/ 1000 \end{pmatrix}; \\ T \ge \left(\dfrac{C_V K_V}{V t^x S^y} \right)^{1/m}; \\ Ra_{необ} \ge Ra, \end{cases} \tag{4}$$

where S_{min}, S_{max} are minimum and maximum values of feed, mm/rev; *D* is diameter of workpiece for processing, mm; n_{min}, n_{max} are minimum and maximum spindle speed rev/min; P_x is axial component of cutting force, N; P_{max} is maximum axial force of machine, N; C_{px}, C_{pz}, C_v are coefficients; x_{px}, y_{px}, n_{px}, x_{pz}, y_{pz}, n_{pz}, *x*, *y*, *m* are exponents; K_{px}, K_{pz}, K_v are correction coefficients; $N_{\partial в}$ is engine power of main drive of the machine, KW; η is efficiency of the main drive of the machine; P_z is tangential component of cutting force, N; *TD* is value of finishing allowance, micron; W_{max}, W_{min} are largest and smallest compliance system, micron/N; P_{max}, P_{min} are maximum and minimum values of cutting force component, which coincides with the direction size, N; $\Delta\varepsilon_y$ is error in mounting of the workpiece, micron; $\Delta_н$ is error in adjusting of the technological system to the maintained size, micron; N is number of parts in the lot, pieces; l_∂ is length of the workpiece, mm; l_i is length of treatment, taking into account the wear rate of the original instrument, mm; u_o is relative tool wear, considering treatment for these conditions, mm.

Outlined multi-objective optimization problem is a multidimensional linear mathematical question that can be solved by using the method of sliding clearance [16].

Taking into account the actual characteristics of the investigated material in determining the fatigue characteristics of the parts is performed by calculating the coefficient of relative machinability of the material, and considering the characteristics of each test material, according to the method presented in [19].

To calculate the generalized relative machinability of part from classification group of construction materials (on which fatigue tests were conducted) benchmark is selected. The ratio of generalized factors investigated and reference material indicates the relative machinability of the material of construction.

This approach extends the use of the proposed mathematical model of the turning process on the constructional materials of alloy chromium steels.

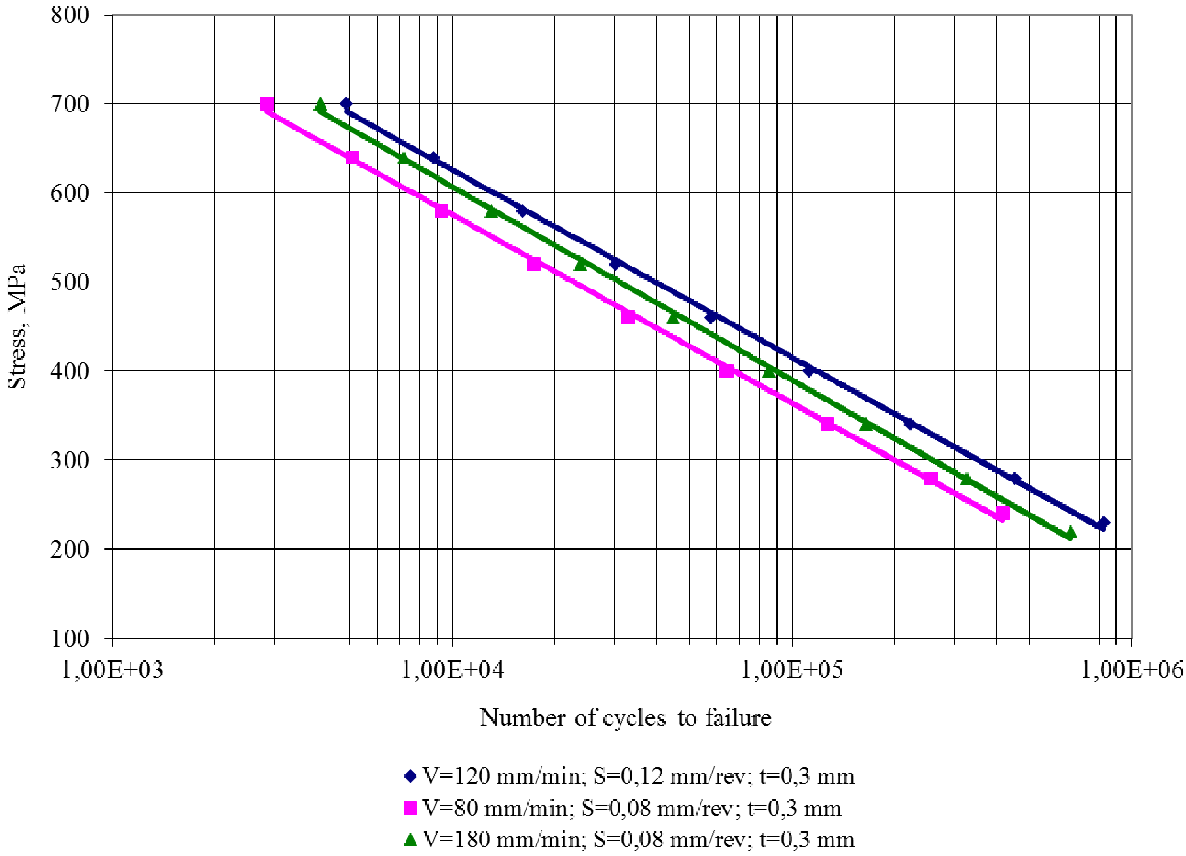

Fig. 6. *Graphical representation of cyclic durability, depending on stress cycle and modes of processing of samples from structural steel 40X GOST 4543-71*

Then complex objective function transformed as follows:

$$C(S,V,s) = K_в\left(a_1 \cdot \left(\frac{N(S,V,s) - N_{\min}}{N_{\max} - N_{\min}}\right) + a_2 \cdot \left(\frac{\Pi(S,V) - \Pi_{\min}}{\Pi_{\max} - \Pi_{\min}}\right)\right), \quad (5)$$

where K_B is coefficient of relative machinability of the material.

Thus using of proposed mathematical model allowed to determine the conditions and modes of lathe processing for parts of 40X GOST 4543-71 steel, which operate under cyclic loading. This finite element method defined stress cycle as 400 MPa.

As a result of optimization of objective function the value for machining modes is received (feed S = 0.12 mm/rev, cutting speed V = 170m /min and cutting depth t = 0.3 mm), which provide maximum cyclic durability of the parts (N = 119000 cycles) and processing performance.

Solving of this optimization problem allows to take into account capability of the equipment and tools, the accuracy of the size of the treated surface and its roughness, and determine the optimum cutting conditions that provide the maximum value of the cyclic durability and performance of material and its productions at a certain operating load.

Conclusions

Impact of the surface layer quality on resistance to fatigue is analyzed. Analysis showed the need for a comprehensive account of surface layer quality parameters through technological conditions of machining.

Experimental study on fatigue was carried out, the results of which revealed the relations of cyclic durability to lathe processing modes, and allowed to develop appropriate mathematical model.

The complex objective function of lathe processing is developed. It consists of two partial optimization criteria – cyclic durability and processing performance, with system limitations (by: feed, speed, strength and power of cutting, precision of cutting, tool life and roughness of the treated surface) and consider the actual characteristics of the part's material.

Outlined multi-criteria optimization task is solved by using the method of sliding clearance, to estimate the best value of feed and cutting speed, ensuring maximum values of cyclic durability and performance of material and parts, as well as their production at a certain operating load.

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