Advances in Engineering Research, volume 177

International Symposium on Engineering and Earth Sciences (ISEES 2018)

Technological Quality Assurance of Hydraulic Cylinder Stock Manufacturing Based on High-Energy Impact on Product Surface

Maksarov V.V.
Department of mechanic engineering
Saint Petersburg Mining University
Saint Petersburg, Russia
maks78.54@mail.ru

Efimov A.E.
Department of mechanic engineering
Saint Petersburg Mining University
Saint Petersburg, Russia
efim-aleks-evgen@mail.ru

Keksin A.I.
Department of mechanic engineering
Saint Petersburg Mining University
Saint Petersburg, Russia
keksin.a@mail.ru

***Abstract*—The article proposes a "stock" - an improved technological process of parts production. During the research it was found that the reason of the failure of hydraulic cylinder is charged rod surface, obtained after the grinding process. This factor leads to intensive wear of the sealing system and subsequent depressurization of hydraulic cylinder. It is possible to eliminate this problem by replacing the grinding process with mechanical treatment with improved dynamic characteristics. It will ensure the macro- and micro-geometric characteristics of surface. One of the main reasons for the deterioration of surface roughness and accuracy is the accumulation of self-oscillation energy, depending on the alternating stages of the chip formation process. The method of high-energy laser irradiation will allow reducing the influence of self-oscillation process on the macro- and micro-geometric parameters.**

Keywords — technological process, surface roughness, accuracy of shape, laser effect, gradient structure, self-oscillation process, dynamic characteristics.

I. INTRODUCTION

Nowadays hydraulic systems are increasingly being used in the production of modern technology, intended for construction, road and mining. As a rule, the conditions in which such hydraulic systems are operated vary over a wide range from operation in difficult climatic conditions and aggressive environments to the perception of increased dynamic loads.

The performance of their assigned functions without interruption under the influence of negative factors is generally reasoned by the quality of manufacture of individual parts of hydraulic system.

In particular, the weakest link is a hydraulic cylinder, which is a part of the executive unit of hydraulic system, consisting of a rod and a liner. As established in works [1, 8], the stock accounts for about 80% of all failures. Most of these violations in the work are reasoned by the destruction of the sealing system of the stock, leading to depressurization of power cylinder.

The violation of the sealing ability is directly related to the technological preparation of the surface of the part "stock" at the round grinding process. The finishing operation leads to the effect of charge, which consists in the saturation of the treated surface with abrasive micro particles from the grinding wheel [6]. At the subsequent stage of thermal diffusion of chromium coating, the incomplete diffusion of chromium atoms will occurs with the metal surface, where there are impregnated abrasive particles. Such surface leads to the following consequences. Incomplete diffusion during operation contributes to the destruction of the protective chrome-plated layer, which in its turn leads to subsequent intensive wear of the sealing system of the "stock" part on the charged surface, under the effect of repeated reciprocating motion. The depressurization of the power hydraulic cylinder causes dust and rock particles to contact the rubbing surfaces of the contact pairs of the stock and the sleeve of the micro-particles, forming corrosion and mechanical damage on them. All these negative factors lead to obvious economic losses, as a result of machine downtime due to the installation and dismantling of a damaged power cylinder.

The improvement of the technological process by replacing the circular grinding operation with more advanced processing methods will allow achieving the success in solving this problem. While considering the power cylinder as an object of the technological process, special attention should be paid to ensuring its micro-geometric characteristics, since these parameters directly affect the performance of the hydraulic system as a whole.

II. Analysis of the Emergence of Self-Oscillatory Process

Nowadays there are many technological solutions to achieve the required surface roughness and accuracy of the product in technological process. As it is known, most of them are based on the suppression of the established self-oscillation process in a closed technological system of mechanical processing (TSMP) through the use of: shock absorbers and seismic vibration dampers; the increase in the stiffness of individual elements of the system; the use of a variety of damping materials in the design of a tool, etc. Applying these methods in practice, it is necessary to deal with the following problems. Firstly, the decrease in the amplitude of the self-oscillation process occurs to a technically established level, which presents in every machining operation. Thus for most of the methods used, the amplitude oscillations at the stage of roughing are in the range from 80 to 120 $m\ s^{-2}$, at half-finished stage - from 50 to 80 $m\ s^{-2}$, at finishing stage - from 30 to 50 $m\ s^{-2}$.

Consequently, the given amplitude parameters will correspond to the surface roughness that does not fit into the limits of permissible values indicated by the technological process. Secondly, using the devices that generate shock perturbations as vibration suppression, there is a probability that the system with a self-oscillatory regime will move from a quasi-stable to an unstable state, since an additional source of energy for its further development will be presented by a blow. As a whole, it will lead to the deterioration of both the surface roughness and the accuracy of the shape of a product.

Based on the above mentioned data, it is possible to identify the problem that is associated with the issues of self-oscillation and the transition to an unstable state at the stage of mechanical processing. In order to introduce the TSMP into the range where small amplitudes of self-oscillations will prevail, it is necessary to understand the physical nature of the occurrence of this process.

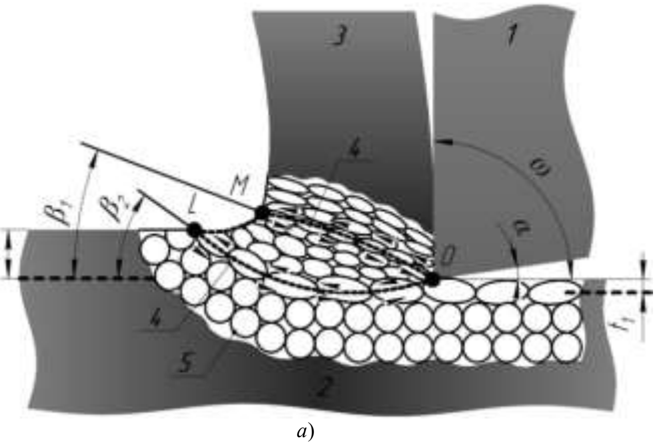
Nowadays there are many hypotheses describing the occurrence of self-oscillations during machining processing. From a physical point of view, the most reasonable is the hypothesis presented by professor V.L. Weitz. The issued suggestion is based on the fact that non-stationary processes during cutting serve as a source for the maintenance of the functioning of self-oscillations in a closed autonomous system. Their presence is caused by the unsteady process of elasto-plastic and temperature deformation of metal, its transition to a fluid state with the formation of a developed shear zone and, as a rule, a cutting layer on the front surface of a tool, leading to the appearance of non-conservative friction forces in contact with the formed chips. It is known that friction has a cyclic process [3, 4, 5], accompanied by the alternate occurrence of spots of adhesion and sliding motion.

At the moment of adhesion of the cut layer with the cutting unit, the divergence of a tool occurs. Then, in order to perform an act of elastic deformation, a certain amount of energy is expended, part of which is dissipated as a result of overcoming the internal friction forces and the corresponding heat generation, without allowing energy to accumulate in the system. These caused disturbances, at the moment when the tool deviates from the equilibrium position, lead to a lag in time of changes in the friction force of the *Q* chips on the tool and the cutting force *P*. These lags are a consequence of the inertia of the friction processes that lead to the occurrence of auto-oscillations throughout the treatment.

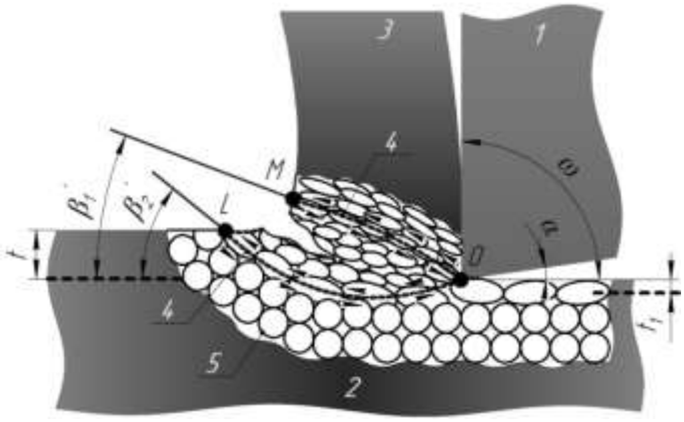
Subsequently, such stress states should arise in the cut layer, thus it will be harder for material to resist active plastic deformation, which will lead to the separation of a cut layer from a workpiece. However, the increase in cyclical nature of the transition between the boundaries of the phases of sliding and setting, which is especially typical for the processing of viscous metals, can lead to the fact that the energy received from oscillations will accumulate in the “tool” subsystem. The last fact is explained by the presence of dissipative properties that do not have time to dissipate the constantly replenishing energy. Such a complex process drives the amplitude of self-oscillations, translating it into an unstable state.

It is possible to dissipate the accumulated energy of self-oscillations from alternating friction processes, as well as to balance the equilibrium between incoming and outgoing energy in a mechanical system due to the periodic destruction of the bond in the contact area between the chips and the tool. To achieve a positive result in this direction was possible with the help of the research based on the study of the process of chip formation. Observing the formation of drain chips, it is possible to follow the gradual formation of elastic, plastic deformation and metal flow in the zone with a developed *OLM* shear area extending in front of the cutting tool.

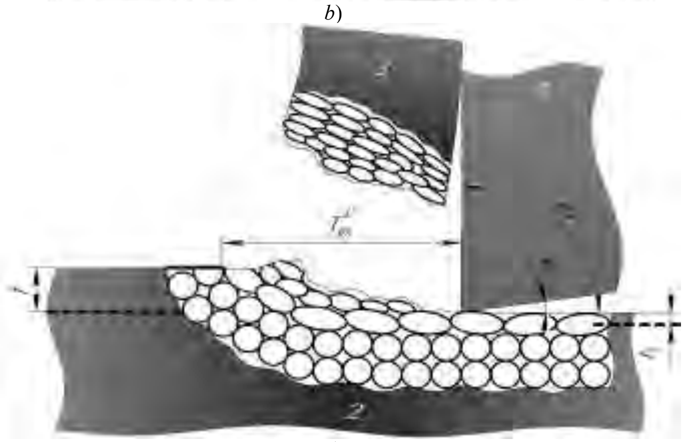
According to the reproduced graphic model with a developed zone (Fig. 1, a), in the areas *OL* and *OM* there are corresponding localized shear planes with an angle of inclination *β1* and *β2*, along which the extrusions of metal round grains into an elliptical shape under the action of compressive and prevailing shear deformations occur.



a)



b)



c)

Fig. 1. The model of the developed zone of plastic deformation OLM (a) with the subsequent formation of a crack (b) and destruction (c), where: 1 - tool; 2 - workpiece; 3 - chips; 4 - localized shear lines; 5 - metal grains; t - the depth of cut; t1 - the hardening depth; α — tool back angle, 8º; ω - cutting angle, 90º; β1 and β2 - shear angles; β1'and β2' - altered shear angles; TexU - energy expended.

It is established [1, 4] that changing the shear angle from $\beta_1 \rightarrow \beta_1'$ and $\beta_2 \rightarrow \beta_2'$ to a positive or negative side will result in a change in the orientation of the elongated grains, which will be subject to additional tensile or compressive stresses. Exceeding the maximum stress limit values will lead to the initiation of a micro-crack in the place of a developed zone (Fig. 1, *b*), the spread of which is possible according to the mechanism of transgranular, intergranular or mixed fracture, depending on the structure of the metal being processed. The crack opens and spreads toward the top of the cutting tool, leading to the formation of new surfaces and the separation of a part of a chip from the cut layer, which will contribute to the rupture of frictional interaction with the cutter (Fig. 1, *c*).

At this moment, a metal free area is formed. During the period of its transition, the tool will consume the incoming T_{ex}^U energy from friction to perform its own oscillatory movements, which will allow avoiding the accumulation of energy and the transition of the technological system into an unstable self-oscillatory process [1].

III. Method for Suppressing Self Oscillation Process

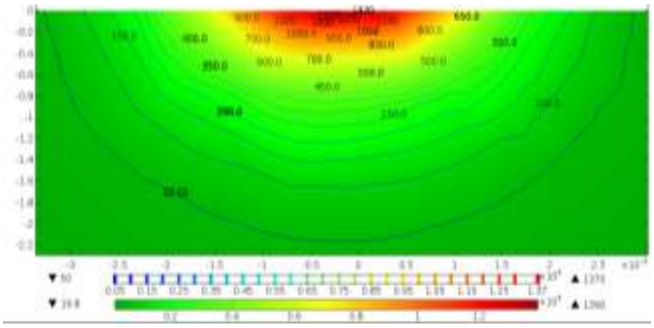
The creation of a local gradient structure in the surface layer of the workpiece by using a preliminary high-energy laser effect applied along a special trajectory will allow changing the angle of localized shear lines in the process of chip formation. It is necessary to note that all the subsequent experimental studies were carried out on *Steel* 45 carbon steel, since the production of the “stock” part is carried out from this type of metal.

The proposed method of dynamic stabilization of the machining process in the production of “stock” parts is divided into several successive stages.

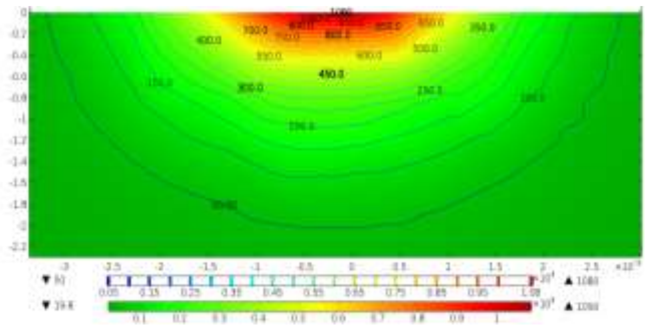
The first stage consists in the application of preliminary local laser irradiation (LLI) on the surface of the workpiece.

When the LLI interacts with the surface of the workpiece, the local area of the workpiece is heated above the temperatures of the critical points of the phase transition of the iron – carbon diagram $A_{c1} \rightarrow A_{c3}$ up to $T_S \rightarrow T_L$ values. In this range of high temperatures, two important points can be highlighted. These include polymorphic transformations in a metal with a change in the type of crystal latitude and the phenomenon of thermal deformation [7]. The last process is associated with the fact that a local metal segment is subjected to heating, which is experiencing structural changes in this area accompanied by an increase in volume. On the other hand, outside the point laser heating, the metal is in a normal state, that is, it is not exposed to temperature effects, and, therefore, presents a barrier for expanding the volume of newly formed structures in the local area. This will entail elastic and then plastic deformations, which, upon cooling, will form a gradient structure with increased residual compressive stresses [9]. As a result, the essence of LLI process is in the creation of a structure that would have distinctive features from the base metal in terms of mechanical properties (in a manner similar to brittle materials) [2].

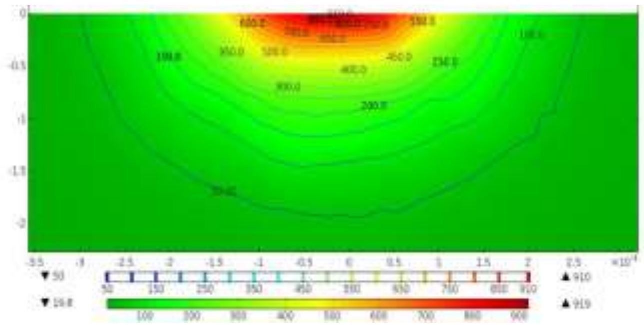
However, the technology of machining processing of the part “stock” consists of three stages. Thus it is necessary for each operation separately to take into account its depth and width of the local gradient structure, which would have smaller values compared to the depth of the cutting surplus [10]. The ignorance of this recommendation will result in the mutual collision of a tool with solid layers of a gradient structure, forming mechanical damage at the cutting edge. In order to avoid the negative effect, the additional virtual experiments were required. For this purpose, in the modern simulation software environment *COMSOL Multiphysics* 5.1 the simulation of temperature fields’ distribution was carried out at the process of LLI (Fig. 2).



1) $P = 2{,}5\ kW$, $V_l = 2000\ mm\ min^{-1}$, $d_s = 4\ mm$



2) $P = 1{,}9\ kW$, $V_l = 2000\ mm\ min^{-1}$, $d_s = 4\ mm$



3) $P = 1{,}5\ kW$, $V_l = 2000\ mm\ min^{-1}$, $d_s = 4\ mm$

Fig. 2. The results of simulation in software environment COMSOL Multiphysics 5.1.

The variable parameter in the simulation model was the laser power, while the velocity of the laser spot V_l and its diameter d_s remained unchanged. The results of the distributed temperature fields over the depth t'_{Gs} and the width h'_{Gs} of LLI are summarized in TABLE I.

TABLE I. THE EFFECT OF LLI MODES ON THE DEPTH AND WIDTH OF SPREAD OF HEAT FIELDS IN MODELING

№	*Power – P, kW*	*Velocity – Vl, mm min-1*	*Spot diameter – ds, mm*	*Depth – t'Gs, mm*	*Width – h'Gs, mm*
1	2.5	2000	4	0.59	3.2
2	1.9	2000	4	0.35	2.6
3	1.5	2000	4	0.15	2.5

The obtained values of the simulated LLI modes were approbated in practice. A laser complex of the LS - 5 model with a power of 5.0 kW and a radiation wavelength of 10.6 µm was used as the emitted source of concentrated energy (Fig. 3).

Fig. 3. Laser setup of LS – 5 model for the formation of a gradient structure, where: 1 - workpiece; 2 - laser head.

Creating the necessary energy conditions for phase transformations, by means of the *LS*-5 laser setup and with subsequent fast cooling of the heated local area deep into the metal, a gradient structure is formed. A subsequent metallographic analysis of the steel sample showed that with the high-energy laser processing of *Steel* 45 (Fig. 4), the structures different from each other are formed in the surface layer.

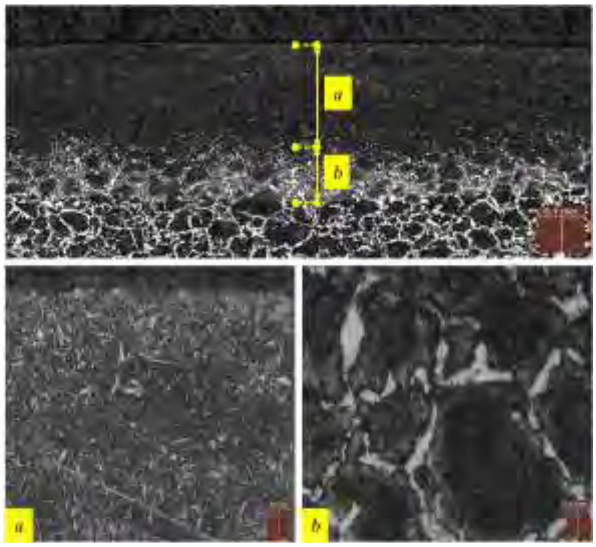


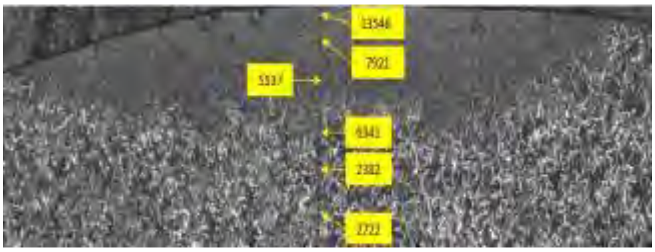
Fig. 4. Gradient structure in Steel 45 (x50) after laser treatment, with an exposure mode: P = 2.1 kW, Vl = 2000 mm min-1, ds = 4 mm.

In the upper part of *a*, the structure of the needled martensite is formed, and in the lower part, as it moves deeper into the metal, the tempering zone *b*, consisting of a troostite-ferrite structure, appears. Closer to the boundary with the source metal, a ferrite latitude is formed. The depth of the gradient structure (Fig. 5) was determined experimentally, using a micro-hardness tester of *PMT-3* model. The results of the experiments are presented in TABLE II.

TABLE II. THE EFFECT OF LLI MODES ON THE DEPTH AND WIDTH OF GRADIENT STRUCTURE DURING THE MEASUREMENT OF MICRO HARDNESS

	Power – P, kW	***Velocity – V_l, mm min^{-1}***	***Spot diameter – d_s, mm***	***Depth – t_{Gs}, mm***	***Width – h_{Gs}, mm***
1	2.5	2000	4	0.68	4.5
2	1.9	2000	4	0.42	4.2
3	1.5	2000	4	0.17	3.75

After a comparative analysis of the simulated and experimental values, it was found that the difference between them is about 12%. This allows judging with complete confidence about the adequacy of the created model of laser action on the processed metal.



1) P = 2,5 kW, Vl = 2000 mm min-1, ds = 4 mm

2) P = 1,9 kW, Vl = 2000 mm min-1, ds = 4 mm

3) P = 1,5 kW, Vl = 2000 mm min-1, ds = 4 mm

Fig. 5. The distribution of micro hardness in the depth formed by gradient structure in *Steel* 45.

A distinctive feature of the formed martensite from the layers not subject to LLI, which is worth paying due attention to, is a different orientation of the structure. In addition, a needled form of martensite can also be considered a positive feature, since it creates additional internal stresses, which increases the tendency of this structure to the brittle fracture mechanism.

The second stage of the method is the implementation of the machining processing of a workpiece with a local gradient structure. When the tool reaches the area with a change in structure, which has a set of zones that are not universal in their structure and mechanical properties, it will lead to the initiation of cracks in them and subsequent destruction under the action of applied cutting forces. As a result, the cut layer in the form of chips from the workpiece will be separated, which will allow removing all-round power loads from the cutting tool. This will cause a change in the nature of the motion of a closed dynamic system from an unstable auto-oscillatory mode to a mode of its own damped oscillations.

This fact is confirmed by the following study with the use of a vibrodiagnostic device of «Prüftechnik MT GmbH» model. For this process, the workpiece was preliminarily exposed to the LS-5 laser complex with radiation modes suitable for finishing mechanical processing: P = 1.5 kW, Vl = 2000 mm min-1, ds = 4 mm. Corresponding to the selected LLI modes, the depth and width of the local gradient structure is presented in TABLE II. Subsequent steps were to install the workpiece on a lathe model JET GH-2040 ZH. The vibration sensors with a perceptual frequency range from 1 Hz to 25 kHz were installed to the cutting tool in two directions corresponding to the tangential Pz and radial cutting force Py. In this case, mechanical processing was performed on cutting conditions: V = 140 m min-1, S = 0.1 mm rev-1, t = 0.2 mm. The results of the recorded values of vibration accelerations from a channel connected in the tangential Pz direction are shown in the oscillogram (Fig. 6).

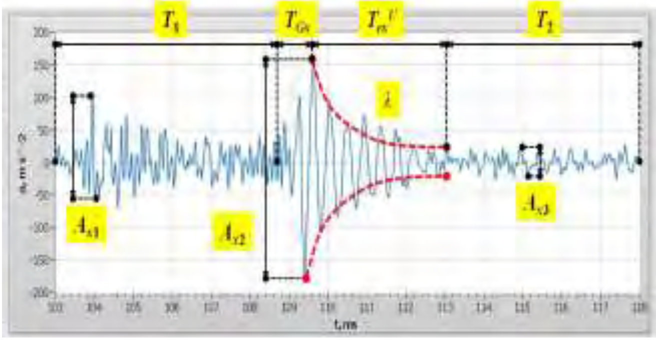


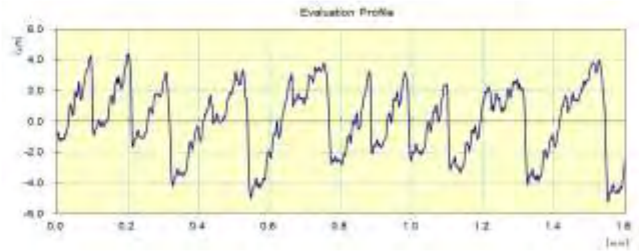
Fig. 6. Oscillogram of vibration accelerations, where: T_1 - processing in raw metal; T_2 - processing after passing through the gradient structure; T_{Gs} - processing in a gradient structure; T_{ex}^U is the period of dissipation of energy into its own damped oscillations; A_{x1} - amplitude of vibration accelerations during normal processing; A_{x2} is the amplitude of natural damped oscillations; A_{x3} - amplitude of vibration accelerations after processing in a gradient structure; λ is the logarithmic decrement.

The presented oscillogram of vibration accelerations shows the following stages of processing. When the cutting tool enters the workpiece, drain chips are formed, which leads to an increase in the amplitude of self-oscillations at the T1 segment to values of Ax1. The transition of the tool into a zone with a gradient structure of TGs leads to the destruction, under the action of a cutting force, of a fragile martensitic structure in the area of chip formation, which causes an increase in amplitude to Ax2. The destruction of the connection between the subsystems “tool” and “workpiece” is accompanied by a change in the motion of the system, which is replaced with a self-oscillating mode with its own damped oscillations.

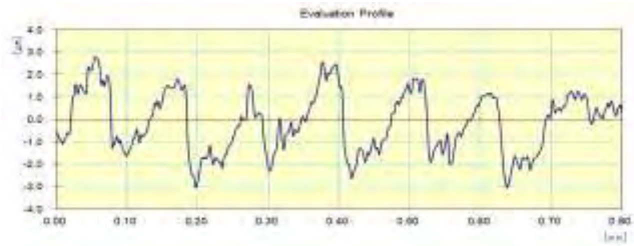
The decrease in the amplitude level is estimated using the logarithmic damping decrement λ. During TexU, the accumulated energy of vibrations is rapidly dissipated due to the presence of dissipative properties up to the amplitude Ax3, leading the closed system to a dynamically stable state indicated in section T2. According to the same principle of operation at all stages of processing a steady suppression of the amplitude of the auto-oscillatory process is observed. The result of the conducted dynamic study of the machining of the workpiece with LLI is the establishment of a reduction in the amplitude of the auto-oscillatory process in comparison with the usual processing by 31 - 45%.

IV. Evaluation of surface roughness and shape accuracy

On the basis of the carried out theoretical and experimental studies, the creation of a local gradient structure, as well as its influence on the dynamic characteristics of the TSMP, the main task was solved. The essence of this task lies in the evaluation of the surface roughness after each stage (rough, semi-finishing, finishing) mechanical processing of the workpiece with LLI. To measure the roughness in the course of the research, a «Surftest SJ-210» profilometer was used. As an example the Fig. 7 shows the profilogram of surface roughness with the use of LLI and without its use.

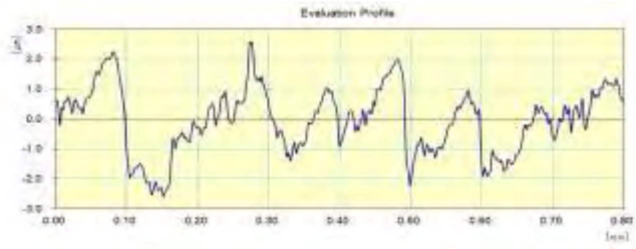


a) Without LLI - Ra = 1.9 µm

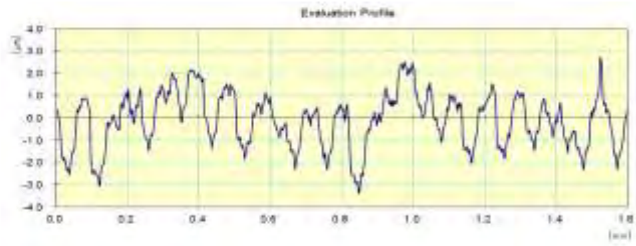


b) With the use of LLI - Ra = 1.16 µm

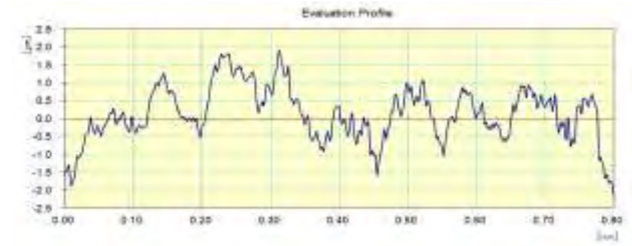
c) Without LLI - Ra = 1.21 µm



d) With the use of LLI - Ra = 0.88 µm



e) Without LLI - Ra = 0.98 µm

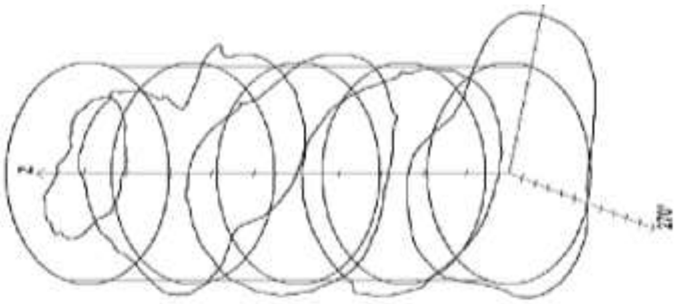


f) With the use of LLI - Ra = 0.59 µm

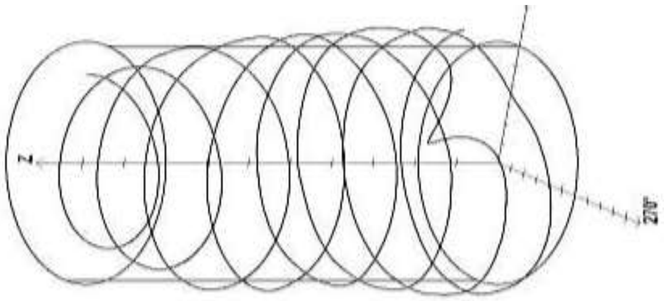
Fig. 7. Profilograms of surface roughness according to the parameter Ra, where the machining modes are: a) and b) roughing processing - V = 80 m min-1,
S = 0.35 mm rev-1, t = 0.7 mm; c) and d) semi-finishing processing - V = 100 m min-1, S = 0.15 mm rev-1, t = 0.45 mm; e) and f) finishing processing - V = 140 m min-1, S = 0.1 mm rev-1, t = 0.2 mm.

From the above mentioned profilograms, a positive tendency to reduce the surface roughness due to the suppression of the amplitude of self-oscillations through the use of the proposed method at all stages of the process is clearly manifested.

In addition to changes in microgeometric indicators, a positive trend has been established towards a decrease in the macrogeometric values of the treated surface. The round meter of the «MMQ 400 CNC» model was used as the measured instrument. An important indicator, from the point of view of the technological process, is the measurement of deviation from the cylindrical shape. The results of accuracy indicators are presented in Fig. 8, a after the usual machining process and using LLI Fig. 8, b.



a) Without LLI – EFZ = 56.2 µm



b) With the use of LLI – EFZ = 35.9 µm

Fig. 8. The deviation from the cylindrical shape.

V. CONCLUSION

The above mentioned set of studies, related both to establishing the influence of dynamic characteristics improved by creating a gradient structure, and assessing their impact on the surface roughness and accuracy of shape of the processed product makes it possible to draw the following conclusions:

- a positive effect from the creation of a gradient structure in surface layer on the suppression of an unstable auto-oscillation process has been established;
- the positive effect of the suppression of the amplitude of the dynamic characteristics on the macro- and microgeometric parameters of the manufactured product was revealed.

To sum up it can be stated that the manufacturing process of the "stock" part can be improved by using the LLI method. This in turn will allow the grinding operation to be removed from the technological process and achieve the specified roughness parameters Ra = 0.63 µm and shape accuracy EFZ = 35.9 µm by suppressing the level of the self-oscillating process at the machining stages of the product with LLI.

Acknowledgment

This article was prepared in the framework of research work on the topic: "Development of a system of dynamic stabilization of the cutting process of dissimilar materials and alloys based on laser local metastability in controlled robotic systems on CNC machines"; state task № 9.10520.2018/11.12 of February 17, 2018.

References

[1] V.V. Maksarov, Ju. Olt, "Improving the precision of manufacturing power hydraulic cylinders of powered roof supports based on a vibration-damping tooling system", Journal of mining institute, vol. 214, pp. 71-84, 2015.

[2] A.G. Grigoriants, I.N. Shiganov, A.I. Misjurs, "Technological processes of laser processing", Tutorial, Moscow, MSTU named after N.E. Bauman, 2006.

[3] M.E. Elyasberg, "Oscillations of metal-cutting machines Theory and practice", SPb.: OKBS, 1993.

[4] V.L. Weitz, "Dynamics and control of chip formation process in mechanical treatment", Monograph, SPb.: SZPI, 2000.

[5] A.E. Efimov, V.V. Maksarov, D.Y. Timofeev, "Modeling dynamic processes at stage of formation of parts previously subjected to high-energy laser effects", IOP Conf. Series: Materials Science and Engineering, vol. 327(4), pp. 34-41, 12 April 2018.

[6] V.V. Maksarov, A.I. Keksin, "Technology of magnetic-abrasive finishing of geometrically-complex products", IOP Conference Series: Materials Science and Engineering, vol. 327(4), pp. 65-70, 12 April 2018.

[7] V.V. Samoylenko, O.G. Lenivtseva, I.A. Polyakov, I.S. Laptev, N.V. Martyushev, "The influence of non-vacuum electron-beam facing on the structure of Ti-Ta layers formed on the surface of VT1-0 alloy", IOP Conf. Series: Materials Science and Engineering, vol. 124(1), pp. 1-5, August 2016.

[8] V.V. Gabov, D.A. Zadkov, A.V. Stebnev, "Evaluation of structure and vari-ables within performance rating of hydraulically powered roof sup-port legs with smooth roof control", Eurasian mining, vol. 2, pp. 37 – 40, 2016.

[9] V.V. Ivancivsky, V.Yu. Skeeba, I.A. Bataev, D.V. Lobanov, N.V. Martyushev, O.V. Sakha, I.V. Khlebova, "The features of steel surface hardening with high energy heating by high frequency currents and shower cooling", IOP Conf. Series: Materials Science and Engineering, vol. 156(1), pp. 10-15, November 2016.

[10] D.Y. Timofeev, E.V. Kosheleva, "Improving the quality of manufacturing parts from titanium alloys using the method of preliminary local plastic deformation", IOP Conference Series: Earth and Environmental Science, vol. 8(87), pp. 1-5, October 2017.