Agronomy Research **17**(S1), 1146–1154, 2019
https://doi.org/10.15159/AR.19.060

Improving the quality of critical tractor parts through the dynamic stabilisation of the manufacturing process in regard to CNC machines

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Abstract. This article focuses on the evaluation of a rod improvement which is considered in detail below. The rod in question is part of an hydraulic cylinder manufacturing process which takes place on CNC machines. The need for ensuring a process improvement in this area arose because the rod often breaks down under operational conditions. It was found that the cause of this is a finishing operation in the existing production process. The effect of charging which occurred during the grinding process brings about the embedding of abrasive particles into the workpiece surface layer. Therefore, at the running-in stage, the mating surfaces on the rod and the system being used to seal the rings both experience intense wear in their contact areas, with this being caused by abrasive microparticles which serves to reduce the performance characteristics of the part in question. However, even if we dispense with the grinding process, ensuring the necessary roughness of $R_a = 0.63$ μm at the machining stage alone will present problems of their own for a number of reasons. First and foremost is the connection with the phenomenon that results in an auto-oscillation processes which is generated by the manufacturing system, as well as the formation of flow chips during machining on CNC machines. In this regard, in order to avoid any negative factors creeping into the process, we propose that a new approach be taken in achieving the necessary surface roughness, one which is based on the suppression of the auto-oscillation process during machining by means of creating a selective metastable structure. At the machining stage, any inhomogeneous structure in the local chip formation area will be destroyed, thereby suppressing the auto-oscillation process and reducing the surface roughness. Eventually, the proposed method will allows the grinding operation to be dispensed with entirely from the manufacturing process.

Key words: production process, local laser impact, metastable structure, machining process system, chip formation, auto-oscillation processes, surface roughness.

INTRODUCTION

At present in mechanical engineering special attention is being given to the tractor industry. The reason for such interest is primarily the high demand for specialised machinery in road and civil construction, in mineral resource-mining enterprises, and also in agriculture. Great demand for special-purpose machinery, as well as the resultant need for spare parts, compels tractor plants to increase their production rates, and this is impossible to accomplish without modernising existing production facilities. For this purpose, the large-scale integration of up-to-date flexible machining cells which are based on the use of CNC machines is presently underway. Such an approach allows output levels to be increased and also the necessary quality parameters to be ensured.

Besides this, as with all machine factories, there are manufacturing problems that can be connected to CNC machines which exist in relation to a wide scope of high-precision tractor parts. For example, the critical part - the rod (C63-3405121 - see Fig. 1) which is part of the C63-3405115 steering linkage hydraulic cylinder for MTZ-2522 tractors - is not an exception in this respect.

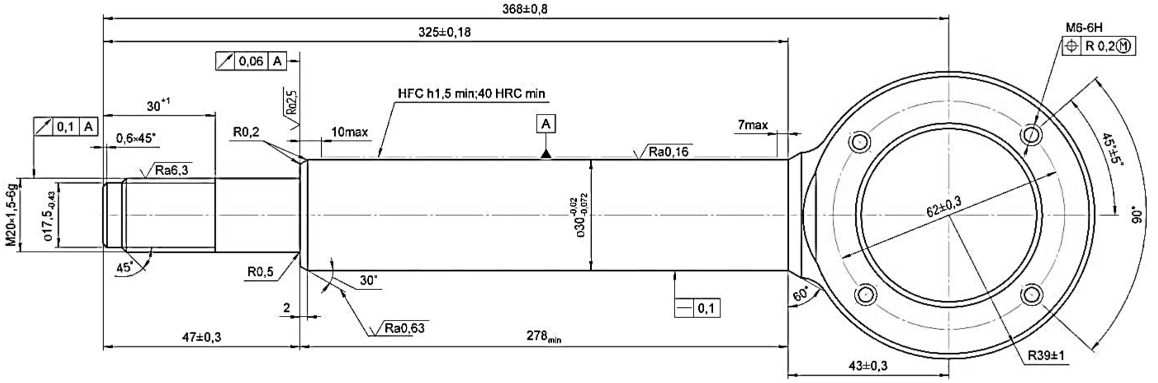


Figure 1. A diagram of rod C63-3405121, part of an hydraulic cylinder.

This item was not chosen at random. The highest single figure in relation to operational failures (about 70%) is caused by this part. Operational failures are caused by breakdowns in the rod sealing system which result in an hydraulic power cylinder seal failure. The loss of the seal is directly connected to rod surface preparation at the manufacturing stage, in spite of the fact that this item must meet strict requirements regarding surface roughness and precision of form (Efimov et al., 2017, Maksarov et al., 2018; Olt et al., 2018).

Firstly, the situation is made more complicated when the surface finish manufacturing parameters that are obtained during the process of precision rod fabrication on CNC machines do not meet the specified standards due to a number of reasons. One of these is metal ductility, which results in the following circumstances: the winding of flow chips on the manufacturing machinery parts; malfunctions in the automatic system which measures the machined part and monitors the state of the cutting tool's levels of wear; and scratching on the machined part's surface and an increase in roughness indicators. Besides all of this, the plastic properties of the metals have a specific impact on the closed *machining process system* (MPS), increasing the amplitude of the auto-oscillation process due to periodic changes in the cutting force and the ambiguity of those changes, increased contact friction between the chip and the cutting tool, and also chip adhesion to the cutting edge (Weitz & Maksarov, 2000). Such physical processes bring about an increase in amplitude and frequency dynamic characteristics, both of which serve to result in the catastrophic wear of the cutting tools, along with surface finish deterioration and a deviation in workpiece form precision (Elyasberg, 1993).

Secondly, the finishing-off which involves a round grinding operation brings about a charging effect which involves surface saturation with abrasive microparticles. In the next stage (thermodiffusion chromising) chromium atoms will not diffuse completely into a metal surface which includes embedded abrasive particles. Such a form of surface manufacture will have the following consequences: in the normal operational process, incomplete chromium diffusion will facilitate the destruction of the protective chromium layer, resulting in heavy wear on the rod sealing system against the surface that has been charged with an abrasive. As a result of the loss of the seal on the power hydraulic cylinder, dust and dirt microparticles will get onto the rod's rubbing surfaces and also onto the bore, resulting in corrosion on the surfaces and mechanical damage to both areas. All of these negative impacts will eventually result in economic losses being suffered thanks to machine downtime that is caused by the removal and reinstallation of a defective power hydraulic cylinder. As a result, in order to solve the problems that have been described above, we have to take a closer look at the aspects involved in the machining process that takes place on CNC machines (Madissoo & Olt, 2011; Stephenson & Agapiou, 2016).

MATERIALS AND METHODS

One possible way of solving the problems that have been outlined above is the dynamic stabilisation of the machining process through the 'workpiece' subsystem (Madissoo et al., 2012). The authors have developed a method which consists of two consecutive stages that will accomplish this objective. The objective of the first stage is to create a metastable structure on the in-process workpiece surface. Since, at present, hydraulic cylinder rods are made of 45-grade steel (Fig. 2), it is possible to create a non-equilibrium structure that is different from the base metal primarily by using local high-energy laser irradiation (Grigoriants, 1989; Sufiiarov et al., 2017; Olt et al., 2018). A 5 kW continuous-wave ytterbium fibre optics laser is used for this purpose.

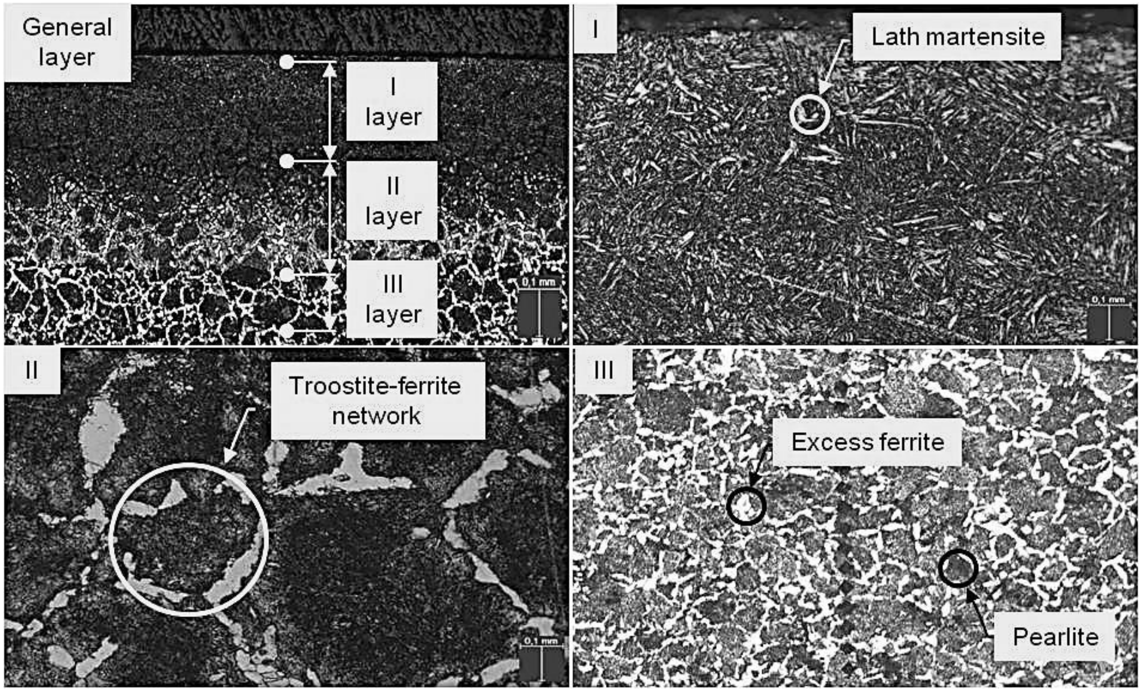


Figure 2. Fabricated metastable structure with (I) being the martensite-structured zone, (II) being the tempered zone (the troostite-ferrite network), and (III) being the initial metal zone.

The energy generated by this process was sufficient to concentrate a threshold radiation power density of $E = 10^4$ W cm^{-2} in a laser beam with a diameter of $d_s = 4$ mm. The initial metal structure that is under consideration consists of two phases: perlite and pro eutectoid ferrite (see (III) in Fig. 2). When laser radiation is applied to the surface of 45-grade carbon steel, a local area of the near-surface workpiece layer experiences ultra-fast heating of approximately 10^3 to 10^4 °C s^{-1} to the temperature point of iron/carbon A_{c1} phase transfer. Ultra-fast heating facilitates a shift of the critical point A_{c1} into a higher temperature range with values of approximately 50–200 °C (Grigoriants et al., 2006). Following this, favourable conditions arise for the simultaneous occurrence of two processes under the influence of the emerging temperature and pressure: the transformation of the ferrite/cementite mixture into austenite, and the transformation of pro-eutectoid ferrite into austenite. A subsequent flash heat ensures the diffusion rearrangement of pro-eutectoid ferrite volume-centred cubic lattice into austenite face-centred cubic lattice. Whereupon the recrystallisation process may lack time in which it can end at the iron/carbon *GS* diagram line, causing a shift of the A_{c3} critical point. Upon the completion of structural transformations, carbon homogenisation takes place. This is completed above the point A_{c3} within the $T_S \rightarrow T_L$ temperature range. This ensures ultra-fast cooling deep into the metal at the rate of $V_c = 400–600$ °C s^{-1}, thereby bringing about a diffusionless martensite transformation in a local area of the metal (see (I) in Fig. 2). A tempered structure takes place closer to the border with the initial metal (see (II) in Fig. 2). Therefore, high-rate cooling brings about an increase in phase hardening, with recovery and recrystallisation processes both slowing down, and austenitic phase defects being inherited more fully. This brings about the crushing of blocks $D = 0.33–0.57\ 10^5$ cm, an increase in dislocation density levels $\rho_d = 9\ 10^{-10}$ cm^2, and an increase in crystal lattice stresses. As a result, the structure that took shape during this process is over-defective and is also prone to brittle failure when compared to the initial structure.

This fact is confirmed by residual stress tests on the resulting metastable structure which were carried out using a STRESSVISION scanner. The map of residual longitudinal strains on the metastable structure surface is shown in Fig. 3.

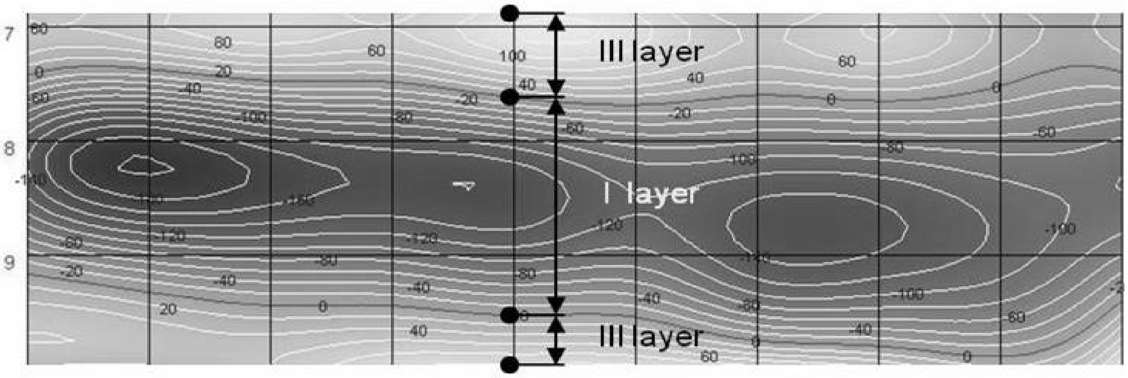


Figure 3. A map of residual strains after local metastable structure-shaping on a workpiece surface under laser impact: $P = 2.5$ kW; $V_l = 2000$ mm min^{-1}; $d_s = 4$ mm.

It has been established that, in zone I, the metastable structure experiences residual compression stresses which are caused by martensite transformation, accompanied by an increase in volume during cooling. Compressive stresses that are equal to -180 MPa take shape closer to the centre of the laser-impacted area. As heat flow advances towards the initial material, compressive stresses drop to -100 MPa. A further advance towards the borders of transitional zone III demonstrates that compressive stresses drop to between -10 MPa and -80 MPa. As compressive stresses move away from the border of zone III, they reach a zero value and change smoothly to tensile stresses that amount to between 20 MPa to 80 MPa. The closer to the initial point - the non-impacted metal - the greater become the tensile stresses, with them reaching a value of 100 MPa. The above results give evidence of a significant inhomogeneity in terms of residual stress distribution in the local area of the irradiated workpiece surface.

Apart from residual stresses, an important parameter is the depth of the created metastable structure that was determined using the COMSOL Multiphysics 5.1 software environment. This software simulated the depth distribution of temperature patterns caused by a laser impact on metal (Fig. 4). A medium-temperature tempering takes place in the area in which the temperature reaches about 350 °C. As is known, structural changes do not occur at temperatures below the above values; therefore, this is the border of the metastable zone - this being its depth.

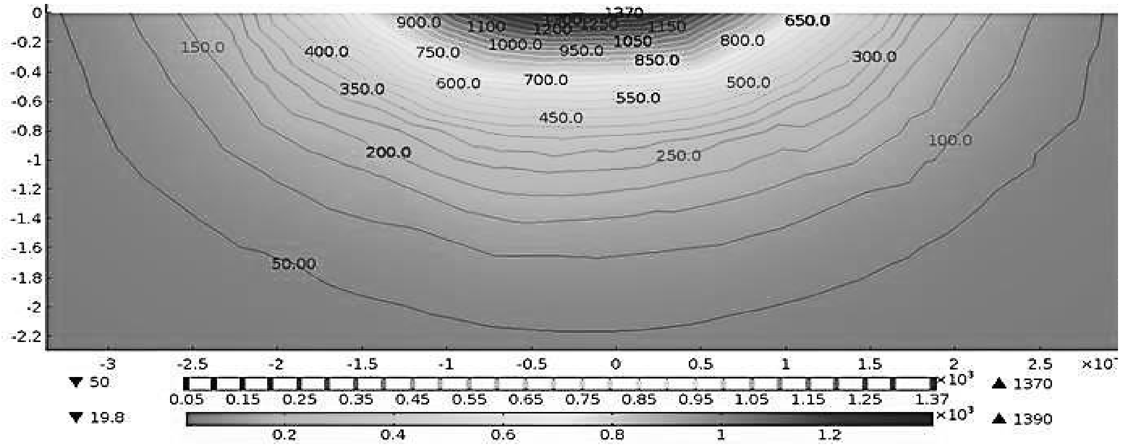


Figure 4. The simulated distribution of temperature patterns under the impact of local laser irradiation where exposure parameters are as follows: $P = 2.5$ kW; $V_l = 2{,}000$ mm min^{-1}; $d_s = 4$ mm. The exposure depth amounted to $t_g' = 0.$ mm.

The results obtained from the computer simulation were confirmed by measuring the in-depth microhardness of the created metastable structure. A dependency between geometric parameters in the altered structure and laser impact characteristics was established by means of comparative analysis (Tabl 1).

Table 1. The influence of irradiation power on impact depth and width for 45-grade steel

No	Spot diameter d_s, mm	Irradiation power P, kW	Machining rate V_l, mm min^{-1}	Gradient structure depth t_g, mm	Calculated gradient structure depth t_g', mm
1	4	2.5	2,000	0.68	0.7
2	4	2.0	2,000	0.34	0.38
3	4	1.5	2,000	0.17	0.15

The task of the second stage was to carry out experimental tests on the machining of a workpiece with a local metastable structure. All of the experimental studies which aimed at the identification of the auto-oscillation process were carried out on an EMCO Concept TURN 250 lathe. A Prüftechnik VIBXPERT vibrodiagnostic instrument was connected to a cutting tool through vibration sensors that were installed in the directions of the tangential cutting force P_z and radial cutting force P_y. Laser impact modes for creating a metastable structure were chosen according to Table 1: with mode 1 for rough machining, mode 2 for semi-finish machining, and mode 3 for final machining. The results of the experimental studies are presented in oscillograms (Fig. 5, a, b, c).

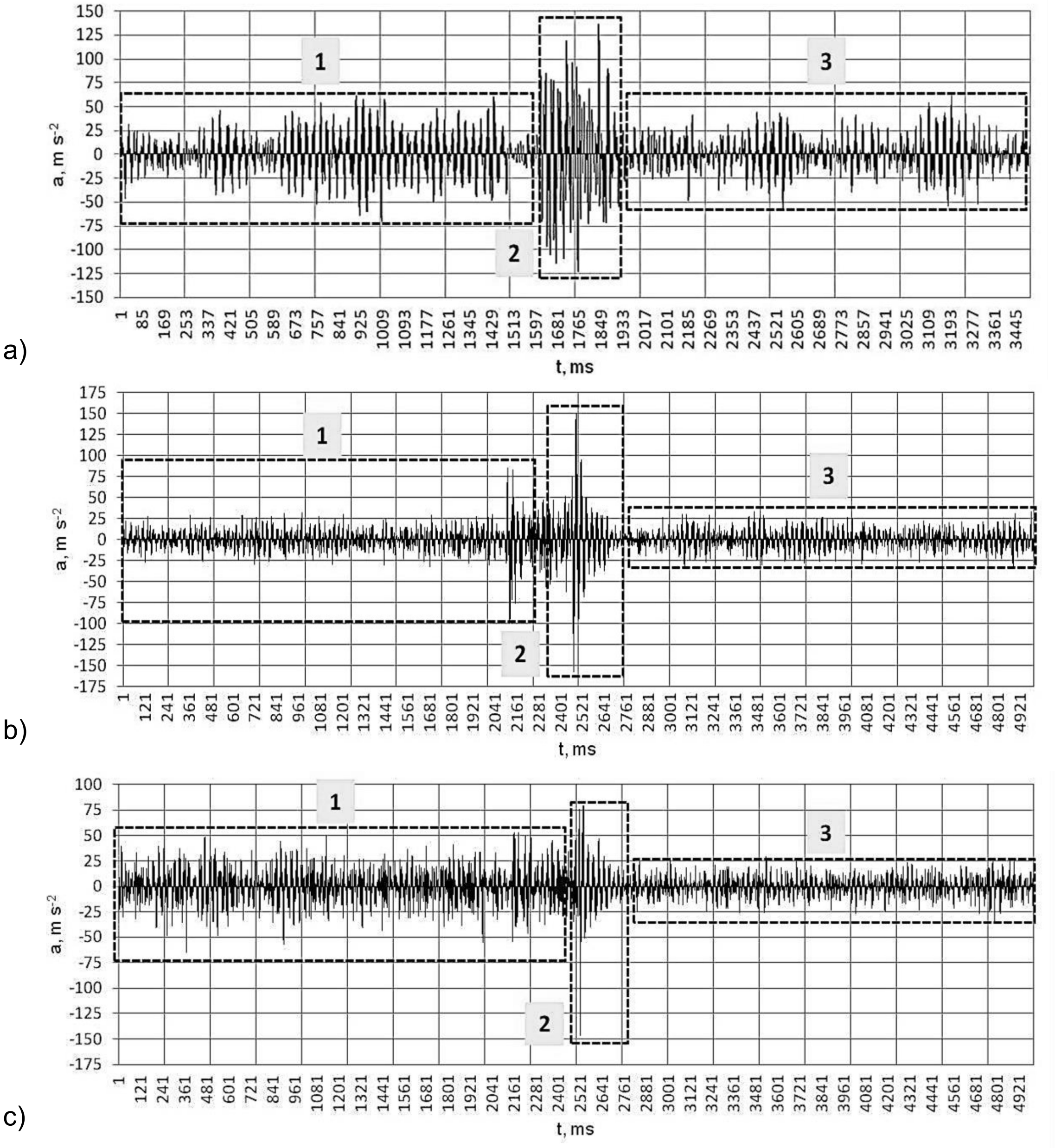


Figure 5. Oscillograms of vibration accelerations during the process of machining a workpiece with a local metastable structure where: *a* is rough machining: $V = 70$ m min^{-1}, $S = 0.35$ mm rev^{-1}, $t = 0.68$ mm; *b* is semi-finish machining: $V = 120$ m min^{-1}, $S = 0.15$ mm rev^{-1}, $t = 0.35$ mm; *c* is finish machining: $V = 160$ m min^{-1}, $S = 0.1$ mm rev^{-1}, and $t = 0.2$mm.

The oscillograms that were obtained are interpreted as follows: as a tool enters the workpiece, an auto-oscillation process arises which is accompanied by an increase in amplitude. This process is marked out as section **1**. When the tool reaches a local metastable zone in which a martensite structure is predominant, a crack is instantly initiated, causing a brittle failure. Then, at the moment of time $t = 1.597$ ms for rough machining, $t = 2.401$ ms for semi-finish machining, and $t = 2.501$ ms for final machining, the 'tool' process subsystem experiences acceleration until the crack encounters the initial ferrite/perlite structure. Such a structure is subject to a ductile failure mechanism that slows down the advance of the crack. Its further development brings about a fully-fledged rupture and the separation of a chip segment from the surface that is being machined. This effect forces the manufacturing system to unlock for between 200–400 ms and causes section **2** to execute free-damped oscillations, thereby dissipating the amplitude of the auto-oscillations that have been established during this period. In other words, this method allows for a short period of time a friction bond to break that has been effected through chip formation between the 'tool' and the 'workpiece' subsystems, allowing the energy in the auto-oscillation process to dissipate where it has been accumulated in the manufacturing system. Subsequent machining is within the range of the auto-oscillation process amplitudes, in section **3**.

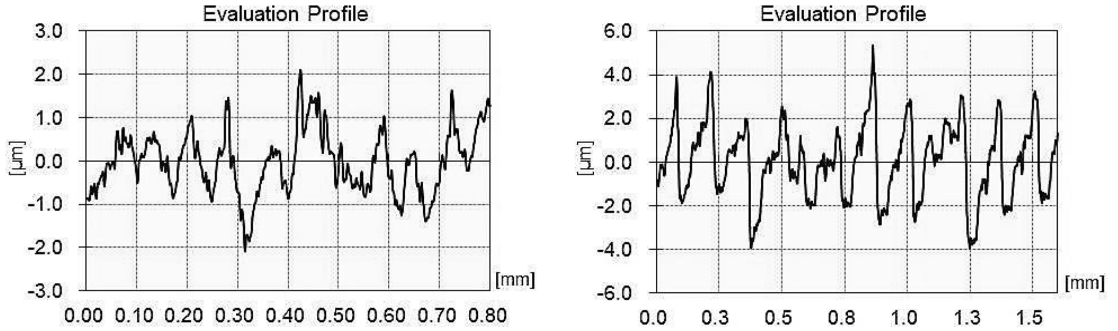
RESULTS AND DISCUSSION

After carrying out dynamic tests that were connected with the machining of the 'rod' part that was preliminarily subjected to local laser action, microgeometric surface characteristics were evaluated. At present, the stylus method is the most precise one available for measuring surface roughness. This surface assessment method was implemented with the help of a Surftest SJ-210 profilometer. Experimental information that could be gathered is presented in the form of the profilograms of machined surfaces of the 'rod' part, following three machining operations in the following modes: finishing operation: $V = 160$ m min^{-1}, $S = 0.1$ mm rev^{-1}, $t = 0.2$ mm (Fig. 6, a, b); semi-finishing operation: $V = 120$ m min^{-1}, $S = 0.15$ mm rev^{-1}, $t = 0.35$ mm (Fig. 6, c, d); rough operation: $V = 70$ m min^{-1}, $S = 0.35$ mm rev^{-1}, and $t = 0.68$ mm (Fig. 6, e, f).

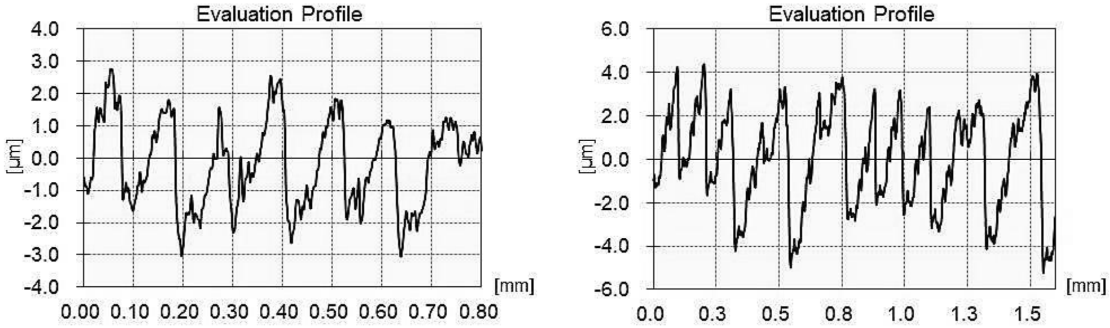
After the experimental tests have been concluded, a tendency is clearly discerned in the profilograms towards a reduction in microgeometric surface characteristics when using the preliminary local laser action method.

CONCLUSIONS

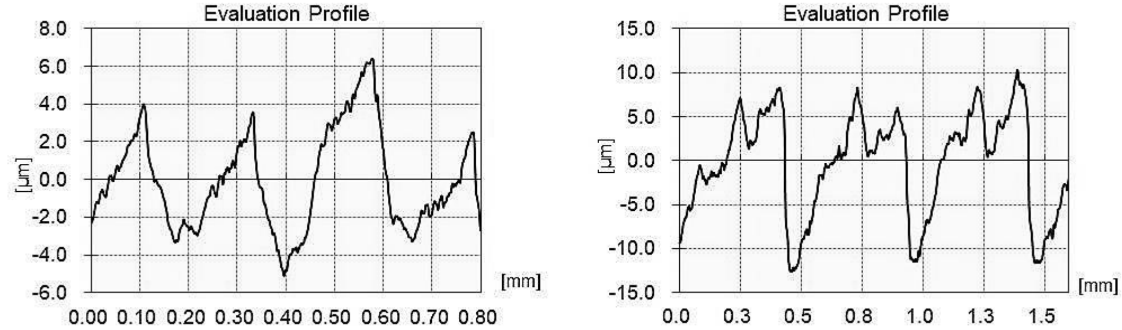
As the authors of this paper have been able to sum up, it is safe to say that the proposed method for ensuring machining-process dynamic stabilisation through the creation of a metastable structure in the 'workpiece' subsystem surface layer allows for a successful reduction in the auto-oscillation processes level by as much as 30%. Reducing amplitude dynamic characteristics during machining allowed, in turn, surface quality characteristics to be improved by as much as 42% and for roughness values to be achieved that were established by the manufacturing process specifications: $R_a = 0.63$ μm. As a result, it turns out that it is possible to dispense with the finishing grinding operation in the existing manufacturing process. It should be noted that the problem of flow chips segmentation has also been solved.



a) With local laser action: $R_a = 0.57$ µm b) Without local laser action: $R_a = 1.373$ µm



c) With local laser action: $R_a = 1.61$ µm d) Without local laser action: $R_a = 1.912$ µm



e) With local laser action: $R_a = 3.123$ µm f) Without local laser action: $R_a = 4.893$ µm

Figure 6. Surface roughness profilograms after machining with and without the utilisation of local laser action.

ACKNOWLEDGEMENTS. This paper has been prepared with the support of the state task No. 9.10520.2018/11.12 in the implementation of the national technological initiative.

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