Modeling dynamic processes at stage of formation of parts previously subjected to high-energy laser effects

A E Efimov, V V Maksarov, D Y Timofeev

Saint-Petersburg Mining University, 21 Line, St. Petersburg, Russia, 199106

E-mail: efim-aleks-evgen@mail.ru

Abstract. The present paper states the impact of a technological system on piece’s roughness and shape accuracy via simulation modeling. For this purpose, a theory was formulated and a mathematical model was generated to justify self-oscillations in a system. The method of oscillations eliminations based on workpiece’s high-energy laser irradiation with the purpose of further processing were suggested in compliance with the adopted theory and model. Modeling the behaviour of a system with the transient phenomenon indicated the tendency of reducing self-oscillations in unstable processing modes, which has a positive effect under the conditions of practical implementation over piece’s roughness and accuracy.

1. Introduction

Nowadays there is a number of various approaches and assumptions concerning the description of shaping the pieces of diverse classifications concerning dynamic processes following the machining process. Basing on this diversity of formulated theories, it is sensible to distinguish the fundamental reasons of the deterioration of piece’s roughness and shape which are inextricably linked with the dynamic view of a tool and piece interaction [1, 2]. Vibrations characterized by a forced nature are of major importance for this process. However, it is probable for such conditions, which will subject vibrations to support by additional energy, to be formed. In such case, a closed-loop physical system will start generating oscillations, which can be described as a self-oscillation process, followed by a continuous increase of vibration amplitude [2, 3].

As far as is known, a generated self-oscillation process exposes a closed-loop physical system to elastic deformations and corresponding deviations of a shape accuracy and continuous growth of vibrations intensity cause the deterioration of surface roughness. In addition, such vibrations have a negative influence on both cutting tool wear and life of a machine tool operating mechanism.

The solution of the problem of piece shaping when considering the given process from the perspective of the dynamic behavior of a closed-loop physical system allows anticipating the occurrence of the self-oscillating mode at the stage of the machining process by the aid of computer simulation [1, 4]. Alongside this, before starting the simulation of a closed-loop physical system, it is crucial to find the causes of the self-oscillating mode triggering and to generate a corresponding mathematical model on the basis of the described theory with regards to the effect which is considered to act as a trigger.
According to famous scientists I. J. Armarego, R.X. Brown, V.A. Kudinov, V.V. Zars, M.E. Elyasberg, V.L. Veits, the physical nature of the self-oscillation process lies in altering the cutting forces evoked by chip formation. However, the greatest success in the given process justification was achieved by M.E. Elyasberg and V.L. Veits [2, 3]. It was denoted in the works of M.E. Elyasberg that the powers delaying can be represented in terms of a two-dimensional model of a piece (Figure 1), having single degree of freedom both in tangential and normal directions accompanied by positional, dissipative and inertial forces as well. A workpiece under this scenario is considered to be completely rigid. Disturbing effect in a quasi-elastic system occurs due to delaying of cutting force $P$ and friction force $Q$. Additional forces $P+\Delta P$ and $Q+\Delta Q$ emerging as a result of their perturbation are conditioned by a specific feature of the process of elastic plastic deformation of the cut down layer and friction of chipping decorticate along the front side of a tool. Then, with the ongoing imbalance of elastic forces, the technological system will be subjected to velocity, which will lead to the storage of vibrational energy due to inertial forces disturbance [3]. The described double-loop system is a simplified model, in which the processes which develop during the chip formation reflect only secondary plastic deformation, which implies that there is interaction between the cut down chipping and a tool. Proceeding from the given constraints, one can conclude that the model is not able to present an adequate and qualitative evaluation of dynamic closed-loop system behaviour. Further development of this theory was implemented by Veits who suggested upgrading and supplementing the existing model by inserting the mechanism of initial metal deformation responsible for the chip formation [1, 2]. Therefore, a complete description of a workpiece and a tool interaction through the cutting process with account of primary and secondary chip distortion required additional model mobility (Figure 2) [2]. The workpiece was altered by obtaining two additional degrees of freedom. Proceeding from the given four-loop model, the equation describing the behaviour of a closed-loop system is represented as differential equations, where: 1, 2 are equations describing tool movements; 3, 4 are equations describing workpiece movements; 5, 6 equations responsible for connecting a tool and a workpiece by means of a rheological model:

**Figure 1.** A tool two-dimensional model, where: 1 is a workpiece; 2 is a tool; 3 is chipping; $m_x$, $m_y$ are reduced masses, $b_x$, $b_y$ are dissipative forces; $c_x$, $c_y$ are rigidity coefficients

**Figure 2.** A quadruple model, where: 1 is a workpiece; 2 are tools; 3 is chipping; $m_x$, $m_y$, $m_u$, $m_w$ are reduced masses, $b_u$, $b_w$ are dissipative forces; $c_u$, $c_w$ are rigidity coefficients
\[
\begin{align*}
0 = & m_x \ddot{x} + b_x \dot{x} + c_x x + \beta_{3x} \cdot (\ddot{x} - \dot{u}) + c_{3x} \cdot (x - u) = Q(1)

0 = & m_y \ddot{y} + b_y \dot{y} + c_y y + \beta_{3y} \cdot (\ddot{y} - \dot{w}) + c_{3y} \cdot (y - w) = P(2)

0 = & m_u \ddot{u} + b_u \dot{u} + c_u u + \beta_{3u} \cdot (\ddot{u} - \dot{x}) + c_{3u} \cdot (u - x) = Q(3)

0 = & m_w \ddot{w} + b_w \dot{w} + c_w w + \beta_{3w} \cdot (\ddot{w} - \dot{y}) + c_{3w} \cdot (w - y) = P(4)

T_P + T_{P1} \cdot (\ddot{x} - \dot{u}) - \left[ k_x \cdot (T_P + T_{P2}) \right] \cdot (\ddot{y} - \dot{w}) + k_{py} \cdot (y - w) -

-\left[ k_x \cdot (T_{P2} - k_{px} \cdot (T_P + T_{P2})) \right] \cdot (\ddot{x} - \dot{u}) = 0

T_Q \ddot{Q} + Q = P - T_{kx} \cdot (\ddot{x} - \dot{u}) - T_{kx2} \cdot (\ddot{y} - \dot{w}) = 0
\end{align*}
\]  

where, $\beta_{3x}$, $\beta_{3y}$, $c_{3x}$, $c_{3y}$ are quasi-elastic and dissipative coefficients in the chip formation zone; $T_P$, $T_Q$ are fixed delays of cutting force; $k_x$ is a coefficient of close loop transmission; $T_{kx}$, $T_{kx2}$, $T_{kx}$ are damping characteristic time from cutting speed fluctuation; $k_{px}$, $k_{py}$, $T_{P1}$, $T_{P2}$ are the coefficients and characteristic time of chip formation.

Thus, the taken mathematical tool assesses the stability (of behaviour) of the technological system, endowed with special characteristics of chip formation and enables one to avoid in practice the operating modes which trigger self-oscillations and deteriorate the surface roughness being formed and pieces shape accuracy [4]. It is worth noting that suppression of the self-oscillating mode emerging during processing can be influenced by changing the chip formation behaviour [1, 2].

2. Method of suppressing self-oscillation process

The most advanced method of suppressing the self-oscillation process in a closed-loop physical system through the chipping elastic and plastic deformation is the application of high-energy laser effects (Figure 3.). The suggested method can be split into two stages: exposure of a workpiece to laser radiation and further machining processing [4, 5].

![Figure 3. Laser machine LC-5 model for the altered structure formation, where: 1 is a workpiece; 2 is a laser head; a is a hardened zone; b is an issuing zone; c is a basic metal; laser modes are $P_l = 1950$ W, $V_l = 2000$ mm/min, $d_s = 4$ mm](image)

The preliminary stage implies the influence of a concentrated emission source on the local workpiece surface which is subjected to high-speed heating from phase-transition point $A_{c1}$→$A_{c3}$ and above up to values $T_c$→$T_l$ [7]. Staying within these temperature intervals, phase transition is accompanied by the processes of thermal distortion resulting in the expansion of the heated workpiece local zone. Changes in volume generate elastic and plastic distortions. For this reason, plastic distortion after being cooled by means of dissipating heat into inner metal pads will contribute to the generation of the structure possessing high values of residual voltage. After final generation of a modernized structure by the mechanism of phase transition, the layer will be endowed with the physical and mechanical properties different from the basic metal [1, 4, 6].
The further stage of machine processing of workpiece $T_1$, having been preliminary subjected to local laser impact, will lead to inserting the cutting tool into zone $T_2$ with a modernized layer (Figure 4) [2, 4]. This will trigger momentary change of the stressed and distortion state in the zone of chip formation being continuous during the whole processing stage. As a result of the leap succession of cutting parameters, the technological system will respond by decreasing the amplitude of fluctuations with values from $A_{x_1}$ to $A_{x_2}$. Thus, the stated phenomenon can be mathematically interpreted as a periodical transition of rheological properties from one level to another on the basis of the knowledge concerning the processes accompanying machine treatment of a workpiece with the altered layer. The introduction of the rheological properties of the chip formation process with regards to the modernized zone into a mathematical model is enabled by the following type of switch:

$$
\Omega(G_t) = \begin{cases} 
G_1 & n \cdot T_2 \leq t < n \cdot T_2 + T_1, \\
G_2 & n \cdot T_2 + T_1 \leq t < (n+1) \cdot T_2, \\
T_2 - T_1 & T_2 - T_1 = \text{const}.
\end{cases}
$$

(2)

where $G_t$ is a parameter denoting rheological properties; $T_2$ is the stage of a modernized layer; $T_1$ is the period of processing in basic metal; $n$ is the quantity of laser effects.

The presence of switch (2) in model (1) will enable one to transit mechanical properties and coefficients from level $G_1$ ($c_1$, $c_2$, $c_3$, $\beta_2$, $\beta_2$) responsible for the basic metal to level $G_2$ ($c_1$, $c_2$, $c_3$, $\beta_2$, $\beta_2$) related to the modernized layer [1, 2]. Further research on the effect of the transition process on suppressing self-oscillations in a closed-loop technological system requires implementing simulation modeling technique.

3. Technological system behavior modeling with account of the modernized layer

Mathematical modeling of the four-loop technological system with account of the transient process is implemented in a software environment NI LabVIEW 2013 SP1. A piecewise-smooth patch according to V.L. Veits’ methodology, which implies exchanging nonlinear characteristics of a broken line with one or several salient points [4], was preliminary used to solve the system of nonlinear differential equations (1). As a result, the system of equations acquires linearity, which enables one to apply Laplace operator method with the view of further calculation. Such transformations of differential equations result in transfer functions. They provide the basis for building a structure consisting of some elements and the interrelations (positive and negative) set between them [3, 4]. After following all successive steps described above, coefficients of the system, available from experiments as well as mechanical properties of the basic metal and a modernized layer are applied to the virtual tool. Having simulated the behaviour of a technological system presented in a virtual oscillogram, the effect of the suppressing self-oscillation process conditioned by the modernized structure (Figure 5) can be observed.
Experimental works on the machine of “Prüftechnik MT GmbH” model linked with vibrodiagnostic research will allow confirming the results of simulated self-oscillations (Figure 6).

To record the vibrations, the vibration detectors with magnetic fastening are installed on the tool in two directions; herewith, measurements are recorded in sync. The outcomes of the conducted experiment have enabled one to detect a 31 – 45% decrease of the self-oscillations level in comparison with the ordinary treatment process. Conversely, self-oscillation impact made on surface roughness and accuracy was assessed on the machines of the “Surftest SJ-210” model and the “MMQ 400 CNC” model respectively. Profilographs and schedules of deviation from surface configuration cylindricity after a typical process of machine treatment are presented in Figure 7 (a) and those ones processed with the application of a localized laser are demonstrated in Figure 7 (b).
Figure 7. Profilographs of roughness and cylindricity, where: a is standard processing Ra = 0.9 μm, EFZ = 56.2 μm; b is processing with the application of laser Ra = 0.55 μm, EFZ = 35.9 μm

4. Conclusion
In conclusion, the major results obtained over the course of the presented work are worth emphasizing. Firstly, theoretical modeling of the behaviour of a closed loop of the technological system with regard to the transition process enabled one to detect the decrease of self-oscillations amplitude during machine treatment, which is a direct consequence of the appropriateness of the constructed model. Secondly, the conducted analysis of the experimental research enabled one to set up a tendency of reducing the indicators of roughness Ra 1.5 – 1.8 times and the indicators of deviation of the form from cylindricity - 1.7 – 2 times during the mechanical treatment of the workpiece with a modernized layer.

References
[1] Olt J, Liivapuu O, Maksarov V, Liyvapuu A and Tärgla T 2016 Mathematical modelling of cutting process system. Springer Proceedings in Mathematics and Statistics. 178 173–186
[2] Weitz W L, Maksarov V V 2000 Dynamics and control of process of chip formation with cutting edge machining. Monograph. (SPb.: SZPI)
[3] Elyasberg M E 1993 Oscillations of metal-cutting machines Theory and practice. (SPb.: OKBS)
[4] Maksarov V V, Viushin R V and Efimov A E 2017 Technological roughness of the surface layer on the basis of modeling of transitional processes Metalworking. 2 39-45
[5] Ivancivsky V V, Skeeba  V Y, Bataev I A, Lobanov D V, Martyushev N V, Sakha O V, Khlebova I V 2016 The features of steel surface hardening with high energy heating by high frequency currents and shower cooling. IOP Conference Series: Materials Science and Engineering 156(1) 012025
[6] Timofeev D Y, Kosheleva E V 2017 Improving the quality of manufacturing parts from titanium alloys using the method of preliminary local plastic deformation. IOP Conference Series: Earth and Environmental Science. 87
[7] Plotnikova N V, Skeeba V Y, Martyushev N V, Miller R A, Rubtsova N S 2016 Formation of high-carbon abrasion-resistant surface layers when high-energy heating by high-frequency currents. *IOP Conference Series: Materials Science and Engineering* **156**(1) 012022