Estimating the Parameters of Deformation Action by Ultrasonic Surface Hardening of Metals

Kharis M Rakhimyanov*, Konstantin Kh Rakhimyanovb, Andrey Kh Rakhimyanovc
Novosibirsk State Technical University, 20 Prospekt K. Marksa, Novosibirsk, 630073, Russia
E-mail: a x.raximyanov@corp.nstu.ru, b raximyanov@corp.nstu.ru, c a.raximyanov@corp.nstu.ru

Abstract. Developing the effective technologies of detail machining greatly depends on understanding the processes laid down in their basis. The technological methods based on electro-physical processes are considered to be attractive. These are the methods of surface plastic deforming which use the energy of ultrasonic oscillations. The peculiarities of these methods are characterized by high intensity and impulse character of the ultrasonic action. The paper presents the results of mathematical modeling of deformation processes under the impact of the ultrasonic tool on the surface layer of metals and alloys. The theoretical approach to studying the process of ultrasonic deforming allowed us to determine the mode parameters of impact and their quantitative correlations with the main characteristics of the deformation process.

Introduction
Ultrasonic plastic deforming as a separate technological method of the hardening and finishing operations is a modification of surface hardening, i.e. diamond smoothening, which is widely used in practice. The presence of ultrasonic oscillations during diamond smoothening leads to intensifying the plastic deformation of the surface layer of the material. It gives the possibility to provide machining at smaller values of static load, which considerably increases the technological perspectives of using such a method [1-7]. To extend further the sphere of using ultrasonic plastic deforming of different materials, from non-ferrous metals and alloys to hardened steels and details with coatings, it is required to determine the range of the mode parameters of the process mentioned. It will allow us to control both hardening and finishing effects in machining.

Theory
The process of ultrasonic plastic deforming should be considered in the following way: the movement of the deformer as a component of the oscillation system after its contact with the machined surface is the excitation of free oscillations [8]. Oscillations are of a harmonic sinusoidal character, which is confirmed by the results of high-speed photography of the process [9]. The movement of the deformer after its contact with the machined surface can be described as follows:

\[
\frac{\partial \Delta(t)}{\partial t} = V_{\kappa_0}(x, t) + \frac{\partial \Delta_0(x, t)}{\partial t} + \frac{\epsilon P(t)}{\rho c S}, \tag{1}
\]
where \( A(t) = A(0,t) \) – the deformer displacement;
\[ V_{k_0} = \frac{\partial A(x,t_0)}{\partial t} \] – the distribution of the oscillation speed at time \( t_0 \) (the deformer contact with the machined surface);
\[ A_0(x,t) = A(x,t_0) \] – the function of displacement along the wave guide length at time \( t_0 \);
\[ F_D(t) \] – the dynamic force, the function of which is determined by deforming conditions, namely, by the character of the depth change of the deformer penetration \( h(t) \) in the machined material. The penetration depth is the difference between the instant deformer displacement \( A(t) \) and the initial value \( A_0 = A(0,t_0) \);
\[ \rho \] – the density of the wave guide material;
\[ c \] – the distribution speed of longitudinal sound waves in the wave guide material;
\[ S \] – the cross section area of the wave guide.

The correlation between the dynamic force \( F_D(t) \) and the deformer movement \( h(t) \) can be presented as:
\[ F_D(t) = \pi \cdot k \cdot HB \cdot d_c \cdot h(t), \] (2)

where \( HB \) – the hardness of the machined material;
\[ k = 1.5 \sim 2.25 \] – the acceleration capacity coefficient;
\[ d_c \] – the diameter of the deformer sphere.

The ultrasonic oscillation system during deforming is tightened to the machined surface by the static force \( F_{ST} \). The correlation between static and dynamic force can be presented in the following way:
\[ F_{ST} \cdot T = \int_{t_0}^{t_2} F_D(t) \cdot dt, \] (3)

where \( T \) – the period of ultrasonic oscillations;
\[ t_2 \] – the time corresponding to the completion of the deformer contact with the machined surface.

By solving the wave equation (1) of the deformer movement, we obtained the main dependencies that characterize the deformation process:
\[ A(t) = A_{max}\left[\sin(\omega t + \varphi_1) - e^{-q\omega t}\sin\varphi_1 + \sin\varphi_0\right]; \] (4)
\[ h(t) = A_{max}\left[\sin(\omega t + \varphi_1) - e^{-q\omega t}\sin\varphi_1\right]; \] (5)
\[ F_D(t) = \pi \cdot k \cdot HB \cdot d_c \cdot A_{max}\left[\sin(\omega t + \varphi_1) - e^{-q\omega t}\sin\varphi_1\right]. \] (6)

where \( A_{max} \) – the amplitude of ultrasonic oscillations;
\( \omega \) – the circular frequency of ultrasonic oscillations;
\[ q = \pi \cdot HB \cdot d_c / \omega \cdot \rho \cdot c \cdot S; \]
\[ \varphi_1 = \varphi_0 + \arctan q; \]
\[ \varphi_0 \] – the trajectory angle corresponding to time \( t_0 \).

The maximum depth of the deformer penetration \( \left( h_{max}\right) \) in the machined material and the peak value of the dynamic force correspond to time \( t_1 \), which value is determined by solving the equation:
\[ \cos(\omega t_1 + \varphi_1) + q \cdot e^{-q\omega t_1}\sin\varphi_1 = 0. \] (7)
Results and Discussion

The theoretical solutions can be presented graphically by the following scheme.

The shape of the stroke impulse (Fig. 1) shows the change in the dynamic force during contacting \((t_0-t_2)\) the deformer with the machined surface. The change in the dynamic force \((F_D)\) during the penetration phase \((t_0-t_1)\) corresponding to the material plastic deforming is described by the dependency (6). The regularities of changes in the dynamic force during the exit phase of the deformer from the contact with the material \((t_1-t_2)\) which corresponds to the elastic relaxation of the elastic deformation of the imprint are not considered in the present investigations but are described in detail in paper [8]. The time of starting the contact \((t_0)\) corresponds to the angle \((\phi_0)\), the time of the maximum penetration of the deformer \((t_1)\) to the angle \((\pi/2)\), the time of the deformer exit from the contact \((t_2)\) to the angle \((\phi_{ex})\) in the period of ultrasonic oscillations. The magnitude of the angle \((\phi_0)\) is determined by the value of the static force \((F_{ST})\) and can be changed from \((-\pi/2)\) to \((+\pi/2)\). When the angle \((\phi_0)\) reaches the minimum value \((-\pi/2)\), the further increase in the static force is not reasonable because the character of deforming the surface ceases to be discrete, which is typical of and necessary for ultrasonic machining. The start of contacting at the trajectory angle of oscillations equal to \((-\pi/2)\) excludes the deformer exit over the surface at the succeeding stroke. The calculated value of the maximum static force depends on conditions and modes of machining (the material hardness, frequency and amplitude of oscillations, deformer diameter). The displacement of the angle \((\phi_0)\) to the maximum values takes place in decreasing the static force \((F_{ST})\). When the angle \((\phi_0)\) reaches the maximum value \((+\pi/2)\) it means that the physical contact between the deformer oscillating with the ultrasonic frequency and the machined surface disappears.

Figures 2 and 3 show the dependency of angle changes \(\phi_0\) and \(\phi_{ex}\) on the oscillation amplitude \(A\) of the deformer at different values of the static force. According to the results of the mathematical model, we can claim that in certain combinations of the deformer oscillation amplitude and the static force it is possible to provide ultrasonic machining at the minimum value of the angle \(\phi_0=(-\pi/2)\). The maximum value of the angle \(\phi_{ex}\) decreases with increasing the amplitude and reducing the static force.
Fig. 2. Influence of the oscillation amplitude and the static force on changing the angle of starting the deformer contact ($\varphi_0$) with the machined material ($HB=2070$ MPa, $f=20$ kHz, $d_c=8$ mm):

1 – $F_{ST}=0$ N; 2 – $F_{ST}=10$ N; 3 – $F_{ST}=25$ N; 4 – $F_{ST}=50$ N; 5 – $F_{ST}=105$ N; 6 – $F_{ST}=210$ N; 7 – $F_{ST}=310$ N; 8 – $F_{ST}=415$ N; 9 – $F_{ST}=510$ N.

The phase of contacting between the deformer and the machined surface during oscillations of the ultrasonic tool will be determined by the difference in angles ($\varphi_{ex} - \varphi_0$).

Fig. 3. Influence of the oscillation amplitude and the static force on changing the angle of completing the deformer contact ($\varphi_{ex}$) with the machined material ($HB=2070$ MPa, $f=20$ kHz, $d_c=8$ mm):

1 – $F_{SY}=0$ N; 2 – $F_{SY}=10$ N; 3 – $F_{SY}=25$ N; 4 – $F_{SY}=50$ N; 5 – $F_{SY}=105$ N; 6 – $F_{SY}=210$ N; 7 – $F_{SY}=310$ N; 8 – $F_{SY}=415$ N; 9 – $F_{SY}=510$ N.
The dependence of the contacting time ($\tau_c$) on the oscillation amplitude at different values of the static force is shown in Figure 4.

![Graph](image_url)

Fig. 4. Dependence of the time of the deformer contact with the machined surface on the ultrasonic oscillation amplitude at different values of the static force ($HB=2070$ MPa, $f=20$ kHz, $d_c=8$ mm):
1 – $F_{ST}=50$ N; 2 – $F_{ST}=100$ N; 3 – $F_{ST}=210$ N; 4 – $F_{ST}=410$ N.

The transformation of the static force ($F_{ST}$) constantly acting during machining into force impulses ($F_D$) of a certain duration and the amplitude value (Fig. 1) provides intensive deforming at moderate values of the static force ($F_{ST}<600$ N) through achieving considerable values ($F_D>2000$ N) by the dynamic force. The correlation between $F_{ST}$ and $F_D$ in the investigated amplitude range is shown in Figure 5. Considering the correlation of the limited values $F_{ST}$ and $F_D$, we can note their insignificant changes (from 3.49 for $A=5$ $\mu$m to 3.58 for $A=15$ $\mu$m).

Figure 5 presents the maximum values of the dynamic force corresponding to completing the penetration phase ($t_1$) of the deformer. Solving the equation of the deformer movement allows us to calculate the value of the dynamic force at any stage both during the penetration phase ($t_0 - t_1$) and the deformer exit ($t_1 - t_2$).
Conclusions

By solving the equation of the deformer movement, oscillating with ultrasonic frequency during its contacting with the hardened surface under certain conditions of machining (the frequency of ultrasonic oscillations $f = 20$ kHz, the hardness of the machined material $HB = 2070$ MPa, the diameter of the deformer sphere $d_c = 8$ mm), we could obtain the quantitative correlation between the static force and the oscillation amplitude. It allowed us to determine the area of the mode parameters for implementing the process as discrete deforming. The quantitative estimation of such process parameters as angles of starting ($\phi_0$) and completion ($\phi_{ex}$) of contacting allows us to find the location of the stroke impulses during ultrasonic oscillations, taking into consideration the time of contact ($\tau_c$), the penetration and exit of the deformer.

The correlation between the maximum value of the dynamic and static force in the investigated mode parameters is found. The considerable excess (by 3.5 times) of the dynamic force over the static force confirms the efficiency of using ultrasonic deforming of thin-walled details, constructions of small hardness and details with coatings.

References

[1]  K.M. Rakhimyanov, I.S. Semenova, Surface state control by ultrasonic plastic deformation at the final machining stage, Materials and Manufacturing Processes. 31 (2016) 764-769.
[2]  V.P. Gileta, Formation of microgeometry of a surface at ultrasonic processing. Proceedings - KORUS 2000: 4th Korea-Russia International Symposium on Science and Technology (27 June - 1 July 2000), Vol. 3, № 866075 (2000) 150-154.
[3]  Kh.M. Rakhimyanov, G.A. Iskhakova, A.Kh. Rakhimyanov, The role of ultrasonic plastic deformation in spark alloying, Fizika I Khimia Obrabotki Materialov. 1 (1996) 68-72.
[4]  V.P. Gileta, G.A. Iskhakova, Investigation into regularities of the surface microgeometry formation during diamond ultrasonic strengthening finishing, Sverkhvttverdy Materialy. 1 (1992) 45-50.
[5]  V.P. Gileta, G.A. Iskhakova, Simulation of regular relief formation in ultrasonic diamond burnishing, Soviet journal of superhard materials. 10 (1988) 64-69.
[6]  G.A. Iskhakova, V.P. Gileta, Formation of the component surface layer in ultrasonic diamond burnishing, Soviet journal of superhard materials. 9 (1987) 66-71.
[7] A.I. Beznedelnyy, V.B. Asanov, V.P. Gileta, Technological inheritance influence on surface layer forming in condition of ultrasonic plastic deformation of hardened steels, Obrabotka metallov (teknologiya, oborudovanie, instrumenty) (in Russian). 4 (2012) 19-22.
[8] O.V. Abramov, V.I. Dobatkin, V.F. Kazantsev, Impact of powerful ultrasonic on the interphase surface of metals, Moscow, 1986.
[9] O.P. Solonenko, A.P. Alkhimov, V.V. Marusin, A.M. Orishich, Kh.M. Rakhimyanov, R.A. Salimov, V.G. Shchukin, V.F. Kosarev, High-Energy Processes of Materials Treatment, Nauka, Novosibirsk, 2000.