Forming a Single Plastic Imprint of the Indenter under Ultrasonic Surface Hardening

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Abstract. The results of the experimental investigation of forming the geometry of a single imprint appearing on the machined surface during a single tool stroke in ultrasonic surface hardening are given. The equations of regression for calculating the geometrical parameters of the imprint depending on the machining modes such as the static force and the diameter of the deforming element are obtained. Unlike the existing models of forming the imprint, the appearance of the material pressed out around the tool during its penetration in the surface layer of the machined detail is taken into account. The pressed-out metal looks like a hill. The equations obtained allow us to determine the height of the hill as well as the depth and diameter of the imprint taking into consideration the hill dimension. The calculation of these parameters is necessary to find out the boundary conditions of starting the appearance of the plastic flow wave under ultrasonic plastic deforming of metals and alloys. These conditions determine the criterion of forming waviness and present the restrictions of the limiting values of feeding and speed in machining the cylindrical surfaces.

Introduction
Nowadays more and more interest in ultrasonic plastic deforming as hardening and finishing operations of details is taken [1-9]. Due to this fact, the questions of the technological quality assurance of the surface under the conditions of discrete deformation impact are considered to be vital. It is known that waviness appears on the machined surface under certain conditions in ultrasonic plastic deforming of natural steels. Paper [10] presents the theoretical investigations on finding out the conditions of appearing waves of plastic flow of metal under the discrete impact by the ultrasonic tool. This condition is a system of inequalities as restrictions determining the limiting values of the speed and feeding under which the waves appear.

\[
\begin{align*}
V & \leq \frac{d_{pl}}{2 \cdot 60 \cdot f}, \\
S & \leq \frac{d_{pl}}{10}
\end{align*}
\]

(1)
where $V$ – the speed of the detail rotation, m per minute; $d_{pl}$ - the diameter of the plastic imprint with the pressed-out metal round the tool during its penetration in the surface, mm, $f$ – the frequency of ultrasonic oscillations of the tool, Hz; $S$ – the feeding, mm per rotation. (Fig. 1).

Conversely, the dependency of the plastic imprint diameter on the mode parameters of machining is not presented in the paper. Traditionally the oscillation amplitude ($A$), static force ($F_{st}$) for pressing the ultrasonic tool to the detail and the diameter of the deforming element ($D_c$) are used as the machining modes influencing the imprint parameters in ultrasonic plastic deforming. The purpose of the paper is estimating the influence of the technological machining modes mentioned above on the geometrical parameters of the imprint.

Fig. 1. Geometrical parameters of a separate imprint formed as a result of plastic flow of material

Experimental Investigation of Forming the Imprint

Goals of the experiment

To exclude the overlapping of the imprints one on another, it is necessary to determine the corresponding modes in machining. Kinematic parameters of machining such as the speed and the feeding affect the location of the imprint centers, and deformation parameters (the amplitude and the frequency of ultrasonic oscillations, the indenter diameter, the static force of pressing the tool to the detail) influence the imprint dimension. According to the deformation model described in Paper [11] the imprint diameter can be determined by the following formula:

$$d = \int_{t_0}^{t} 2\sqrt{D_c \cdot h_1(t)} dt - \left( h_{max} - \int_{t_1}^{t_2} 2\sqrt{D_c \cdot h_2(t)} dt \right),$$

(2)

where $h_1(t)$ and $h_2(t)$ – the functions which describe the depth change of the tool penetration in the respective phase of its direct and reverse movement in the material, $D_c$ - the diameter of the spherical part of the indenter, $h_{max}$ – the maximum depth of the indenter penetration, $t_0$ – the time during which the contact of the deforming element with the detail surface takes place, $t_1$ – the time of the maximum penetration, $t_2$ – the time of completing the contact between the deforming tool and the machined surface.

Calculating the imprint dimensions, it is necessary to take into account the tool sliding during its contact with the machined surface, as a result of which the imprint takes the form of ellipse. Paper [12] traces the correlation between the imprint parameters and geometrical, kinematic and force parameters of ultrasonic plastic deforming. According to the paper mentioned, in machining the cylindrical surface the ellipse dimensions depend on the indenter geometry (the diameter of the spherical part, $r$), the time of contact between the detail and the tool ($\Delta t$), the speed of the detail rotation ($V_d$), the depth of the
deformer penetration \((h)\) as well as elastic and plastic properties of the machined surface (Fig. 2). In this case the dimensions of the ellipse semi-axes are determined by the following equations:

\[
a \approx \sqrt{D_y (2h + h_y) - h^2}
\]

\[
b \approx \sqrt{D_y (2h + h_y) - h^2 + 0.5 \cdot \Delta t \cdot V_d}
\]

where the parameters \(r, h, h_y, h \) are calculated by the deformation model \([11]\). The calculations showed that the value of the large ellipse axis \((2b)\) did not exceed two diameters of the imprint \((d_{im})\) at a maximum possible speed of the detail rotation, taking into consideration the real conditions of machining.

\[
\begin{align*}
2A & \quad 2b \\
D_y & \quad d_{im}
\end{align*}
\]

Fig. 2. The scheme of contacting between the ultrasonic tool and the cylindrical surface (a – in the longitudinal section, b – in the cross section)

Because the model used does not take into account the appearance of the pressed-out material around the imprint, we can consider that it is necessary to provide the distance of more than \(2d_{im}\) between the imprints in order to ensure the absence of overlapping the imprints. As the dimension of the pressed-out material is small in comparison with the imprint diameter, the distance in \(3d_{im}\) will be sufficient. The distance between the imprints in the feeding direction must be not less than \(2d_{im}\). Thus, to obtain separate imprints on the machined surface in ultrasonic plastic deforming, the condition mentioned above can be presented in the following way:

\[
\begin{align*}
l_v & \geq 3d_{im} \\
l_s & \geq 2d_{im}
\end{align*}
\]

where \(l_v\) – the distance between imprints in the direction of the speed of the detail rotation, \(l_s\) – the distance between the imprints in the direction of feeding.

The distance between the imprints in the direction of the speed is presented in Paper \([12]\) as follows:

\[
l_v = \frac{V}{60 \cdot f},
\]

where \(f\) – the frequency of ultrasonic oscillations, Hz.

The value of feeding for one revolution is the distance \(l_s\). Thus, the restriction for ultrasonic plastic deforming modes, which provide the formation of separate imprints on the machined surface, can be presented by the following system of inequalities through simple transformations:
\begin{align*}
V & \geq 3d_{im} \cdot 60f \\
S & \geq 2d_{im}
\end{align*} \quad (7)

**Methods of the Experiment**

Cylindrical samples with a diameter of 50 mm made from steel were chosen for carrying out the experiment. The samples were preliminary turned to obtain the initial roughness of the surface Ra 2.5.

The sample machining with the successive change in each parameter (the static force – from 50 to 250 N and the deformer diameter – from 5 to 20 mm) was provided on the modes chosen according to the restriction (Eq.6). Unchanged parameters in machining were the frequency of ultrasonic oscillations (22 kHz), the amplitude (20 micrometers), the speed of the detail rotation (280 m per min) and the feeding (1.3 mm per rotation).

The typical picture of the machined surface obtained by microscope Nikon MM-400 is presented in Fig. 3. Separate imprints in the form of ellipse, evenly distributed on the surface at a distance $l_V$ and $l_S$ in the directions $V$ and $S$ respectively, can be seen in the picture.

The profile diagrams (5 for each mode) were taken from each surface after machining, after that the geometrical parameters of the imprint were determined. The typical profile diagram with the geometrical parameters is presented in Fig. 4.

Fig. 3. Typical view of the surface after ultrasonic plastic deforming at modes providing the formation of separate imprints without overlapping
Fig. 4. Typical profile diagram of a single imprint with the pressed-out metal

Results and Discussion

According to the experimental results the equations of regression for calculating $d_{pl}$, $h_{pl}$, $h_{im}$ were obtained under different mode parameters.

The diameter of the plastic imprint ($d_{pl}$) depending on the static force ($F_{st}$) and the deformer diameter is determined according to one of the Eq.8-10.

$$d_{pl} = -0.0051 F_{st}^2 + 3.155 F_{st} + 504.7 \quad (Dc=20 \text{ mm}) \quad R^2 = 0.9955,$$

$$d_{pl} = -0.0037 F_{st}^2 + 2.6491 F_{st} + 474.7 \quad (Dc=10 \text{ mm}) \quad R^2 = 0.9972. \quad (8)$$

$$d_{pl} = -0.0039 F_{st}^2 + 2.6214 F_{st} + 417.4 \quad (Dc=5 \text{ mm}) \quad R^2 = 0.9944.$$

The dependence of the imprint depth ($h_{im}$) on the static force and the deformer diameter is presented as:

$$h_{im} = -8 \times 10^{-5} F_{st}^2 + 0.0654 F_{st} + 2.0348 \quad (Dc=20 \text{ mm}) \quad R^2 = 0.9938,$$

$$h_{im} = -4 \times 10^{-5} F_{st}^2 + 0.0463 F_{st} + 2.0148 \quad (Dc=10 \text{ mm}) \quad R^2 = 0.9968, \quad (9)$$

$$h_{im} = -4 \times 10^{-5} F_{st}^2 + 0.0411 F_{st} + 1.3569 \quad (Dc=5 \text{ mm}) \quad R^2 = 0.9933.$$

The dependence of the pressed-out material height ($h_{pl}$) on the static force and the deformer diameter is described in the following way:

$$h_{pl} = -4 \times 10^{-5} F_{st}^2 + 0.0273 F_{st} + 1.1044 \quad (Dc=20 \text{ mm}) \quad R^2 = 0.9940,$$

$$h_{pl} = -2 \times 10^{-5} F_{st}^2 + 0.0199 F_{st} + 1.0583 \quad (Dc=10 \text{ mm}) \quad R^2 = 0.9969, \quad (10)$$

$$h_{pl} = -2 \times 10^{-5} F_{st}^2 + 0.0179 F_{st} + 0.755 \quad (Dc=5 \text{ mm}) \quad R^2 = 0.9935.$$

Conclusions

The obtained equations (8-10) describe the dependence of the geometrical parameters of the imprint on the static force and the indenter diameter during ultrasonic plastic deforming taking into account the appearance of the pressed-out material. A high validity of approximation allows us to use these dependences in engineering calculations. The established interconnections between the geometrical parameters of the imprint and machining modes give the possibility to determine the boundary condition of forming the waviness during ultrasonic plastic deforming.

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