Physical mechanism of ultrasonic machining

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Abstract. In this paper, the main aspects of ultrasonic machining of constructional materials are considered. Influence of coolant on surface parameters is studied. Results of experiments on ultrasonic lathe cutting with application of tangential vibrations and with use of coolant are considered.

1. Introduction
Ultrasonic machining has been known and studied for several decades [1], but so far it is not a wide spread technology because of some complexities of the implementation and certain cutting speed limits. Advantages of ultrasonic machining and its influence on machined surface finish, cutting tool durability and forces arising during machining, are controversial. At the same time, new constructional materials, up-to-date machine tool design and modern machining technologies allow to improve efficiency of ultrasonic machining. In particular, new ultrasonic units are capable of automatically adjusting frequency of ultrasonic generator on resonant frequency thus drastically reducing power consumption. There are also some new specific tasks where machining to precise (nanometric) tolerances producing ultra-high quality (e.g. machining of glass or other optical materials) which makes manufacturers to use ultrasonic machining technologies neglecting its disadvantages [2].

In present paper, the general theory of ultrasonic machining is considered. In addition, the common results of experiments on ultrasonic lathe cutting of stainless steel with application of tangential vibrations and with use of coolant are given.

2. Theoretical background
The main advantage of the ultrasonic cutting can be explained by size reduction of plastic deformation zone within the material being machined. Figure 1 shows the plastic deformation zones during conventional (a) and ultrasonic (b) lathe turning. The shapes of these zones were revealed by analysis of frames of high-speed shooting [3]. It is noticeable that shear angle becomes significantly larger when applying ultrasonic vibration to the cutting tool. It is evidence that chip shrinkage and plastic deformation rate of the cut off layer drastically fall. Since there is no cutting edge build-up, the ultrasonic lathe turning provides a better surface roughness even at low cutting speed.
In Figure 2, the surfaces of workpieces made of stainless steel X5CrTi17 machined without (a) and with (b) application of ultrasonic vibration, are shown. It can be seen that in conventional cutting, the particles of the edge build-up remain on the machined surface. In addition, the cutting tool point trace in this case is not so distinct in comparison with ultrasonic cutting.

The main reasons of beneficial effect of ultrasonic cutting technologies are as follows: frictional force reduction in the cutting zone; cutting edge build-up elimination; initialization of dislocation movements in the machined material; better coolant access into the cutting zone; higher machining process stability.

In Figure 3, the forces acting to the chip element from the direction of rake surface of cutting tool are schematically shown. The vector of resulting force $R$ formed by frictional force $F$ and normal pressure force $N$ can be decomposed to the components $P_{\text{shear}}$ and $P_{\text{compr}}$ that are parallel and perpendicular to the shear line, respectively. The $P_{\text{shear}}$ component generates a shearing force and a bending moment $M$ arising in the chip and increases with distance between cutting edge and point of resulting force $R$ on the rake surface. On the other hand, the compressing component $P_{\text{compr}}$ prevents tension tending to arise under action of the moment $M$ in the chip’s layer located close to the rake surface, and inhibits crack-opening. These forces can be described as follows [4]:

$$M(t) = P_{\text{shear}} \cdot L = \frac{P_{\text{shear}} V}{\xi} \cdot \sin (\pi - \delta - \Phi) \cdot \kappa \quad (1)$$

$$P_{\text{shear}} = R \cdot \cos (\rho + \Phi - \gamma) \quad (2)$$
where $L$ is the bending moment arm, mm; $V$ — cutting speed, m/min; $\xi$ — chip shrinkage coefficient; $t$ — time, min; $\delta$ — cutting angle which is equal to $\pi/2 - \gamma$; $\rho$ — friction angle; $\gamma$ — rake angle; $\phi$ — shear angle; $\kappa$ — coefficient that takes into account a speed decrease of point of resulting force $R$ in comparison with the chip movement speed, $\kappa < 0.5$.

As equation (1) shows, at a first approximation, the bending moment grows proportionally to the time taken by the chip’s element generation. The $P_{\text{shear}}$ component is also time-dependent, but in a more complex way that $M$ does, because of irregular distribution of pressure over the rake surface.

Figure 3. Forces acting to the element of chip from the direction of the rake surface (a) and stress distribution diagram on the shear plane (b)

The bending moment tends to turn the element of chip counterclockwise, thus generating the tensile stresses in the chip near the cutter’s rake surface and compressing stresses on the opposite side of the chip. The maximum tensile stresses arise at the cutting tool point. Consequently, under action of the bending moment, the chip’s element tends to come off the bulk workpiece near the tool point. The compressing stresses of $P_{\text{compr}}$ partly compensate the tensile stresses tending to stop the crack-opening on the chip’s surface oriented to the rake surface of the cutter. This compensation rate depends on the friction ratio between the chip and rake surface [5].

Applying of the ultrasonic vibration changes the force balance shown in Figure 3a. This happens because of significant decrease of friction angle $\rho$, increase shear angle and size of chip’s element, changing friction forces and normal pressure. These overall changes don’t allow the precise calculating of new value of $P_{\text{compr}}$, though the experiments [6—8] bring out clearly that applying of the ultrasonic vibration, under otherwise equal conditions, the radial and normal components of cutting force drastically decrease making it possible to machine non-rigid workpieces. Decrease of the chip’s deformation rate also shows that when using the ultrasonic vibration the compressing force’s contribution drastically decreases. Keeping the $P_{\text{compr}}$ constant with increasing the $M$ results in expanding the area of tensile stress on the shear plane and makes the chip to move easier. During the conventional cutting, the plastic deformation causes the concentration of dislocations and microcracks in the machined material before the cutting edge, which also form the macrocracks (including the advancing crack) in the chip under the action of tensile stress from the direction of the cutting edge. The surfaces of cracks near the tool’s point remain rudimentary because there is no contact between them and atmospheric oxygen or coolant. As the chip moves to the area of compressing stresses, the microcracks can be healed by the molecular forces [9]. These forces also inhibit the advancing crack growth which makes the chip to remove easier.

Thus, the tangential ultrasonic will act efficiently if the forced vibration velocity exceeds the cutting speed value. In this case, the gap between the tool’s rake surface and machined material arises
periodically. If coolant is not used, the atmospheric oxygen is delivered into this gap, thus oxidizing the surfaces of microcracks and somewhat preventing the healing of the cracks. When the ultrasonic vibration applied, the chip becomes continuous (flow chip) decreasing the cutting and friction forces as well as chip strain hardening.

3. Experimental procedure

3.1. Microhardness of chip surface

The experiments show that using coolant with ultrasonic vibration applied helps to improve the machined surface roughness, increase the tool durability, change the chip hardness in a more efficient way than even when machining with ultrasonic vibration without coolant. In conventional cutting, the elements of chip adjacent to the rake surface have the highest hardness [10]. In Figure 4, the results of the chip microhardness measurement after the ultrasonic machining, are shown. The line 1 means the ultrasonic lathe turning without coolant, while the line 2 illustrates the ultrasonic machining using aqueous soap solution.

The graph analysis shows that when machining without coolant, the chip's hardness measured at the depth of up to 170 μm exceeds the initial hardness of machined material (166 HB) by a mean of 50% (line 1). When using coolant, the chip's hardness at the depth from the surface of 25 μm is much lower than the initial hardness (line 2). At the same time, the surface roughness when using coolant is at least 2 times lower. So it can believed that during ultrasonic lathe turning, the coolant application increases the microcracks generation rate on the chip's surface near the point of the cutter.

The experiments also show that when ultrasonic machining with coolant, the influence of secondary plastic deformation on the texture of chip becomes minimal. In Figure 5, the microslices of chips produced by the ultrasonic cutting are shown. In Figure 5a, a slight impact of the secondary deformation zone to the chip's texture can be observed, i.e. the chip's texture at the rake surface is slightly deformed in the direction opposite to the one of chip movement. In Figure 5b such deformations are not present. Moreover, the chip edge destruction is clearly visible, confirming the presence of microcracks located near the cutting edge. This leads to the chip microhardness reduction, as it was shown in Figure 4.
3.2. Influence of coolant on ultrasonic machining by measuring vibrations

To study the influence of coolant on ultrasonic cutting process, the vibration acceleration was measured. In this experiment, an accelerometer was installed to the back center of lathe machine. The vibration acceleration was recorded within the range of tangential ultrasonic vibrations which is equal to 23.5 kHz.

In Figure 6, a sample waveform of amplitude spectrum of the vibration acceleration when ultrasonic machining with coolant, is shown. The spectral maximum at the frequency of 23.5 kHz matches the frequency of the forced vibration being applied to the lathe cutting tool.

Despite dissipation of ultrasonic energy in the elastic system of the machine tool, it could be fixed on the back center [11]. In Figure 6, the low-frequency region depicts the components produced by cutting and friction processes. The vibration acceleration amplitudes of these processes are 6 times lower than one generated by the ultrasonic vibrations. In another experiment (without coolant), the signal amplitude at the frequency of 23.5 kHz was 4—5 times lower because of worsening contact between the cutter and the workpiece.

In addition, machine oil have been used as a coolant. In this case, the amplitude of the ultrasonic component is 2 times lower than when aqueous soap solution was used. Thus, the coolant composition, its viscosity and wetting capability strongly influence the machining process. The coolant viscosity effects the speed of filling of microcracks that open when the rake surface goes away from the bulk material, while wetting capability provides penetration of coolant into the microcracks by the capillary effect. The liquid penetrating into the microcracks creates the wedging effect (the wedging pressure in microcracks of about 1 nm may reach 100 N/mm²), but it doesn't have a dominant influence on the chip hardness reduction during ultrasonic machining. The experimental studies also
showed that even long-term application of ultrasonic vibration to the surface of part being completely dipped in the coolant, doesn't significantly influence the surface microhardness.

4. Summary
The chip surface microhardness reduction is caused by three conditions: cutting, ultrasonic vibration and coolant application. The ultrasonic vibration not only prevents chip adhesion, but also provides coolant supply into microcracks, including advancing crack. This causes the generation of liquid wedge allowing the growth of advancing crack and its movement by the cutting surface. The same mechanism leads to the chip material dispergation, finally resulting in the chip microhardness reduction.

The advancing crack allows chip to come off the bulk material not only by shear but also by its pressing out of the surface being machined.

The liquid wedge can drastically increase actual rake angle, although its value depends on geometry of advancing crack, so the final workpiece surface is produced by real cutting edge of the cutter. Under these condition, the dynamic rigidity of elastic system where the cutting process is performed, becomes crucial.

A big disadvantage of ultrasonic technologies in machining processes is cutting speed limits. Although the experiments have shown that ultrasonic machining with coolant is very promising and must be extensively studied.

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