AUTO-RESONANT ULTRASONIC CUTTING OF MATERIALS FOR MACHINERY MANUFACTURE

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Abstract. Technologies that use ultrasonic vibration to intensify processes are gaining wide recognition in scientific and industrial environments. By superimposing high frequency vibration, the basic mechanical behaviour of many processes and materials is seen to be transformed. This leads to the development of new machines and processes with advanced characteristics. Important results of processing some materials with auto-resonance ultrasonic nano-turning are presented in this article. After ultrasonic processing of materials, nanostructured near-surface layers emerge. These structures are responsible for the micromechanical characteristics of the material. The developed technology allows processing of various hard-to-machine materials with the obtainment of a surface of heightened geometrical and mechanical properties and with minimum power inputs and material capacity. The article presents the results of the analysis of the structure of component surface layers subjected to ultrasonic turning with an auto-resonant device. The presented photographs demonstrate the formation of nanostructures in the thin surface layers of the processed sample materials. It is shown that auto-resonant ultrasonic treatment leads to hardening of the surface layers. At present, there are some new devices for vibro-cutting and smoothing of materials, such as titan and titanic alloys, heat resisting steels, ceramics, and various kinds of glass, pig-iron, and others. Moreover, owing to the well-directed processing of the near-surface layers of materials, where systems of nanostructures are formed, a number of intermediate operations, such as, for instance, grinding and polishing, turn out to be excluded from the technological processes, and this, as a consequence, enables one to lower the manufacture cost price.

Keywords: auto-resonance, ultrasonic, material processing, effectiveness, surface profile, family of devices.

Introduction

Ultrasonic methods of treatment [1] consist in superimposing ultrasonic vibrations on the machining tool. These techniques are used in the processes of plastic deformation, metal cutting, wiredrawing and tube drawing, etc. Imposition of such vibrations results in a significant reduction in static forces required for the technological process. These effects are explained in [2-4], based on analysis of nonlinear rheological models.

Surface treatment by ultrasonic plastic deformation methods, apart from improving the quality of the surface, creates a nano-structured surface layer with improved mechanical properties (yield strength, tensile strength, and surface hardness, etc.).

Stable and predictable results of ultrasonic processing can be achieved only by implementation of the most effective resonant modes under the circumstances of a changing technological loading on the ultrasound system. There are some problems which arise due to the nonlinearity of the load process, causing the specific distortion of the amplitude-frequency characteristics of the oscillating system [1; 5]. The way out of these problems is to use a self-oscillating drive circuit, implemented by inclusion of a positive feedback loop that produces an exciting impact by non-linear conversion of the signal proportional to the movement of the working body of the machine. When auto-resonant turning, the most effective resonance condition is being supported automatically in the system regardless of any parameter variations such as the parameters of the oscillating system and of technological load.

Fig. 1 shows the diagram of the device [6]: 1 – work-piece; 2 – cutter; 3 – waveguide concentrator that transmits vibrations from the piezoelectric elements 4 to a cutter. A concentrator is fixed in the casing 5 which is installed in the tool holder 7 of the lathe through the use of the bracket 6. Power supply to piezoceramic elements is made through a feedback loop comprising the sensor 8 to detect the vibrations of one of the elements of the vibrating system, as well as a phase shifter F and a nonlinear amplifier 9. At a sufficiently large coefficient in the initial section of the amplifier characteristic, self-excitation of the vibrations occurs, while the level of the output voltage limit defines the amplitude of the settled oscillations.

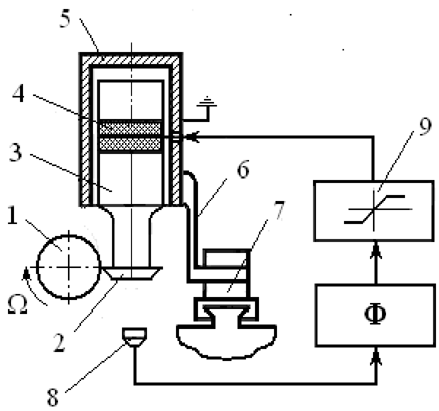

Fig. 1. **Diagram of the device**

At certain phase of the feedback signal, determined by the phase shifter F, resonance vibrations are excited, with the frequency depending, in particular, on the process load. If the phase shift is chosen so that the phase difference between the vibrations of the cutter and exciting force produced by the vibration exciter corresponds to resonant frequency, the device will implement resonant oscillations at variations of technological load and vibration system parameters over a wide range.

Materials and methods

1. Reduction of the cutting forces takes place at metal-turning of all metals: aluminum, copper, bronze, stainless and heat resistant steels, and titanium, etc. At ultrasound cutting, the cutting forces get lower when the cutting speeds $v < a\omega$, where a, w are an amplitude and frequency of vibrations of the instrument correspondingly. The reason for reducing the cutting force is in changing the nature of the cutting process. Ultrasonic cutting appears to be a periodic vibro-impact process with a frequency ω [1; 3; 5; 7] wherein the cutter-work-piece interaction is accompanied by periodic breaks of the contact between the cutter and the work-piece. Furthermore, the amplitude of the pulse of emerging forces equals to the force of traditional cutting, while the pulse duration depends on the ratio of the cutting speed v and the amplitude $a\omega$ of the cutter vibration speed. A measured in the experiments cutting force is a period average value of impulse forces.

Ultrasonic vibration significantly alters the nature of the removing chips [8]. Even when processing materials, conventional turning of which is accompanied by the formation of brittle chips, ultrasonic cutting causes formation of plastic continuous chips without burrs and irregularities. Fig. 2 shows photographs of chips in the traditional process (a) and ultrasonic turning (b) of the steel work-piece.

a)

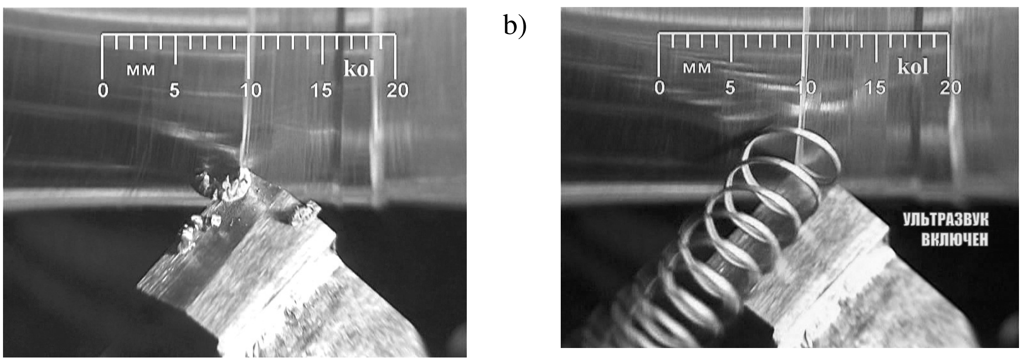

Fig. 2. **Chips in:** a – traditional process; b – ultrasonic turning

The ultrasonic vibration technology substantially reduces the amount of the minimum possible cutting layer. Since, while processing carbon and stainless steels we managed to perform turning with feed 0.05 mm·rev^{-1} and a cutting depth of 0.015 mm.

Imposition of ultrasonic vibration changes radically the geometric structure of the resulting surface. Fig. 3-a, b show photographs of the surfaces of hardened steel work-pieces treated by traditional (right pieces) and ultrasonic turning (left fragments) at the cutting speeds of 10 m·min^{-1} (a) and 60 m·min^{-1} (b), and 0.05 mm·rev^{-1}. A radical difference in the quality of the surfaces is obvious. The surface obtained by ultrasonic turning has a strictly regular structure. This is confirmed by the surface profilogram (Fig. 3-c), which right part has been obtained by traditional turning with the left part – by ultrasonic turning. Recurrent troughs with the feed steps of 0.05 mm, which can be observed in both parts of the profilogram, represent a trace of the top of the cutter. In Fig. 3-b a segment of ultrasonic turning demonstrates periodic turning prints due to the periodic (with the frequency of 20 kHz) interactions between the tool and the work-piece. Also, such prints, if enlarged, are observed on the surface (Fig. 3-a), but here they are not visible as their step is much less due to the low cutting speed.

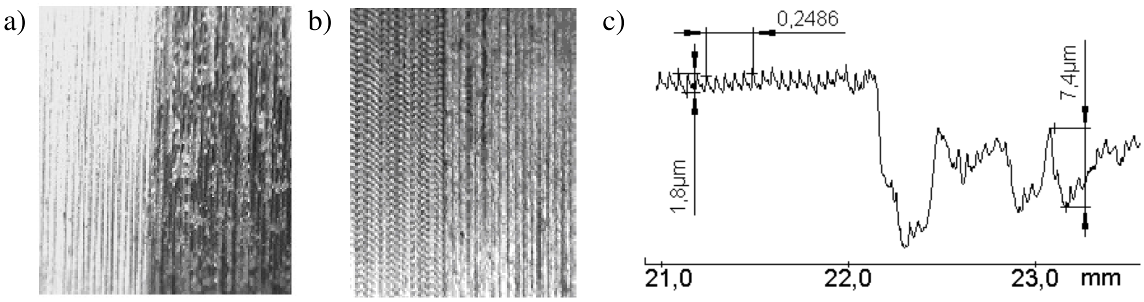

Fig. 3. **Hardened steel:** a, b – treated surfaces; c – example of profilogram

Such difference in the cutting results is caused by the change of the cutting regime. In traditional cutting under the continuous interaction between the tool and the work-piece, the plastic deformation zone is located in the vicinity of the cutting edges and propagates with the cutting speed. This zone is full of micro-cracks, distributed randomly. As a result, the surface has irregular distribution of micro-roughness. Ultrasonic cutting is the result of periodic micro impacts, succeeding with a high frequency. Because of the high repetition frequency and the short period of pulses the plastic deformation zone is concentrated in a small neighborhood of the top of the tool, and the zone is not saturated with microcracks that do not have time to grow. Therefore, a track of the cutter on the surface of the work-piece illustrates factually an imprint of its shape, as shown in Fig. 3-b.

2. The analysis of almost all processed metals revealed nanostructuring of surface layers after the ultrasonic treatment. At auto-resonant ultrasound proccessing, the efficiency of the impact on the surface layer increases considerably [8; 9]. Occurrence of nano structures and their regularity in the surface layer at auto-resonant cutting is visible clearly in Fig. 4. In order to get information about the structuring and surface state after auto-resonant ultrasonic treatment we manufactured thin sections and took photos of them, both optical (Neofot-32) and electron microscopic (scanning electron microscope Tescan).

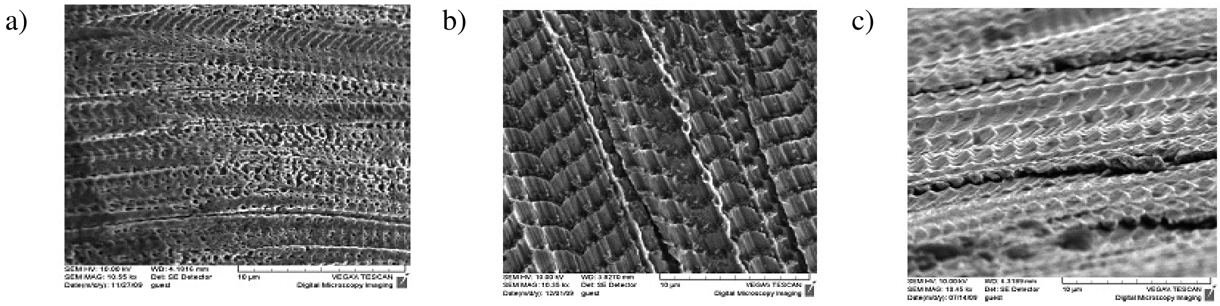

Fig. 4. **Reinforcing nanostructures:** a – copper; b – brass; c – steel

By using a scanning electron microscope Tescan, fractographic studies were conducted. The size of coherent scattering regions was measured by the X-ray diffractometer. The photos show etched (and therefore blunt) cracks, deformational jumps, and the "second" phase. However, the grain structure at etching has not revealed itself. Perhaps, this is due to the fact that during formation of the chip so many defects originated in the crystal lattice of the grains that their total elastic energy appeared to be comparable with the energy of the boundaries. As a result, both grains and boundaries are being etched with the same speeds.

Measurement of the size of the coherent scattering areas showed that the grain size ranges from 50 nm to 0.3 μm or more. Wide dimensional variation is attributed to the following circumstance: close to the free surfaces formed by cracks motion, the elastic stress fields from mesodefects that were responsible for the deformation of grinding structure relaxed. This resulted in the fact that within these areas the grain structure of the original material apparently preserved, with the grain size being about 1 μm. Whereas in other areas, where the deformation took place with maintaining continuity, the grain structure was milled further up to nano-crystalline.

Measurements and calculation of micro-hardness of the work-pieces were performed after auto-resonant cutting. All samples subjected to ultrasonic treatment had an increase in micro-hardness from 10 to 80 %. Testing of micro-hardness by indentation method was done on the PMT-3 device and is standardized (RF State Standard 9450-60).

Mechanical models of lattice structures of the type shown in Fig. 4 are considered in [8]. Fig. 5 demonstrates a family of devices to implement auto-resonant ultrasonic turning and smoothing, including ultrasonic vibration generators and devices for machining of various types, including, of course, CNC machine tools.

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Fig. 5 demonstrates a family of devices to implement auto-resonant ultrasonic turning and smoothing, including ultrasonic vibration generators and devices for machining of various types, including, of course, CNC machine tools.

Fig. 5. **Devices for auto-resonant ultrasonic turning and smoothing**

Obtaining of highly specific, efficient (in terms of physical and mechanical properties) nano-crystalline structures at auto-resonant ultrasonic cutting of steel, copper and brass indicates the importance of learning and developing of the method of ultrasonic cutting and smoothing of materials.

For decades experts have known and been discussing a method of ultrasonic cutting and smoothing, used to reduce roughness and increase micro-hardness, as well as to form compressive residual stress. However, still there are no effective theoretical models enabling to harden materials in auto-resonant cutting, no efficient techniques based on the current state of research in this area.

Among the mechanical properties of nano-clusters and nanostructures noteworthy are high hardness and high ductility. First of all, the nanostructure hardness should increase with a decrease in the cluster size. On the other hand, in the case of the nanometer size, the diffusion slip of the nano-crystallites is of great importance, and the strain rate increases significantly. Thus, the strength properties of the nano-material are determined by the ratio between the yield strength (strength) and strain rate. As another factor boosting the strain rate, one should regard the increase in the diffusion coefficient with decreasing the cluster size.

Results and discussion

Classical technologies of ultrasonic material processing allow one to obtain surface and subsurface nanostructures, but only auto-resonant technologies can ensure the stability of structuring and obtaining the desired properties of the surface and nanocrystalline structures with certain parameters.

Obtaining of specific and highly efficient (in terms of physical and mechanical properties) nanocrystalline structures at auto-resonant ultrasonic cutting steel copper and brass points to the importance of learning and developing of a method of ultrasonic cutting and smoothing of materials.

The devices designed for turning enable one to perform the following:

1. Significantly reduce the cutting force;
2. Handle technologically nonrigid products not using supporting lunettes;
3. Create reinforced near-surface layers of the material;
4. Conduct superhard and brittle material turning;
5. Improve the accuracy of product processing;
6. Increase tool life;
7. Improve the surface finish and quality;
8. Eliminate the possibility of self-oscillation when cutting.

A number of other industrial auto-resonant ultrasonic devices have been elaborated.

- Pecialized equipment for surface hardening of work-pieces to improve the surface finish and to harden the surface layer of the material.
- Wire drawing device to manufacture such delicate wires as thin filaments of precious metals.
- Ultrasonic apparatus for dimensional processing of holes and cavities of arbitrary shape in brittle materials.

In parallel with the industrial auto-resonant ultrasonic equipment we also propose household devices.

- *Putty knife*: intended for surface plastering and filling; eliminates putty sticking to the instrument; allows obtaining thin layers of putty; provides its better adhesion to the working surface. A similar device can be used to apply creams with cosmetic and medicinal purposes.
- *Knife:* intended for cutting products prone to crumpling, squashing and sticking (fresh bread, cheese, cakes, etc.).
- *Chisel*: designed for wood carving and channeling in wood products, for example, sockets for mortise locks.
- *Kreytsmeysel*: intended for cutting metal, for example, for engraving on metallic surfaces or making moulds for precious metal jewelry.
- *Blade sharpening device for knives and scalpels*: sharpens blades simultaneously with hardening of the material by plastic deformation (whetting) of the blades. It can be used, for example, for whetting the scythe blades.

This list can be greatly extended, first of all, due to various vibration technological machines operating in sub-ultrasound-frequency bands [10].

Conclusions

Auto-resonant ultrasound technologies alongside with vibration technologies in general are characterized by high performance, efficiency and productivity, as they allow obtaining the maximum possible amplitudes of the working body (or other defining characteristics) with minimum power expenditures.

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