J Electroceram (2008) 20:187–192
DOI 10.1007/s10832-007-9132-4

Piezoelectric actuator design for ultrasonically assisted deep hole drilling

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Received: 28 November 2006 / Accepted: 17 April 2007 / Published online: 4 May 2007

Abstract From different chipping machining processes it is known that a superposition of the cutting kinematics with additional vibration energy increases material removal rate and tool life. Concerning the deep drilling process in the scope of smallest diameters from 0.9 to 6 mm insights to this so called hybrid processes are still awaited. Preliminary investigations indicated that here is high, so far unused potential. The goal of current research is an increase in effectiveness of the deep hole drilling process by superimposing additional vibration energy in ultrasonic frequency range by means of a piezoelectric transducer and low-frequency vibrations in the range of acoustic frequencies as well. Positive effects can appear in a couple of areas, e.g. achievable surface quality, feeding force, drilling torque, shape and length of chips, feasibility of machining ceramic materials and tool wear. This paper describes mainly the ultrasound conform design of the vibration unit. Furthermore issues of contactless energy transfer into a rotating tool and model based design of piezoelectric transducers will be addressed.

Keywords Deep hole drilling · Ultrasonically assisted machining · Superimposed vibrations · Model based design of piezoelectric transducers

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1 Introduction

Many technical products, for example fuel-injection systems, oilways and air ducts, demand the creation of deep holes with small diameters. In creating holes with ratios of length to diameter up to 200 the deep hole drilling process is the only adopted technique. The tools used in deep drilling, the so called gun drills, are carbide tools with one cutting edge. Figure 1 shows a conventional gun drill. The right part of the gun drill will be screwed at the spindle of the machine tool. A borehole goes through the whole gun drill, which pipelines the cooling lubricant with high pressure towards the workpiece. Besides cooling the chip transport out of the borehole is an important function of the lubricant. As can be seen in Fig. 1 the drill has a continuous corrugation for the purpose of chip transport. The coolant-chip-mixture coming out of the tool is absorbed by the box for boring chips.

A disadvantage of gun drills is their scrawny shape and the susceptibility to fracture caused by the brittle carbide cutting material. The main reason for drill breakage are long and badly winded chips which are hard to transport away. The higher the rate of feed is the longer and worse winded chips are produced. Through this the drilling torque raises vigorously and the drill can break easily. This is meant to be the main productivity limitation of the deep hole drilling process.

By superposition of ultrasonic vibrations it is expected that shorter chips will be produced which can be transported away more easily. Because of the decreasing drilling torque the rate of feed and therefore the productivity could be raised significantly. This is especially valid in the case of machining with tools of smallest diameters, which — as a result of its shape — can be loaded stronger in the axial direction than in the circumferential direction. This gives the

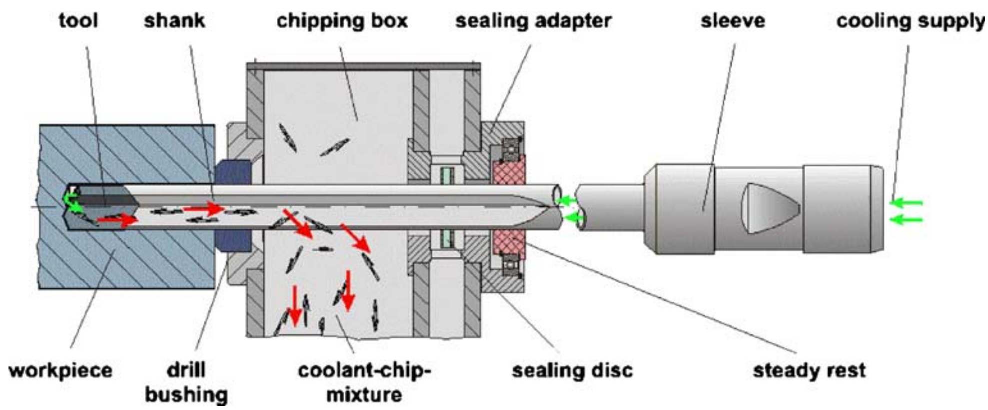


Fig. 1 Gun drill in the deep hole drilling process [1]

possibility of a decisive increase in rate of feed without the danger of tool damage as a result of too high drilling torque. Altogether the following positive effects could be realized:

- Better surface quality
- Lower drilling torque
- Smaller chips (prevention of tool breakage)
- Better chip transportation away from the tool tip
- Lower tool wear
- Feasibility of machining ceramic material

2 Preliminary investigations

It has been demonstrated in pilot surveys that the process limitations described above (low rate of feed) can be moved significantly. Figure 2 shows exemplarily the results attained with a conventional ultrasonic actuator normally used in the field of plastics welding. In each case a gun drill with 2 mm in diameter came into operation.

Further results from this simple setup indicate that by superposition of vibrations the tool was loaded stronger in axial direction than without additional vibrations (32 to 40 N instead of 25 to 30 N without ultrasound). In contrast the drilling torque which finally could lead to drill breakage was decreased enormously. Moreover the investigations show that by the use of additional vibration energy shorter chips are produced than in conventional deep hole drilling. Consequently chip deadlocks with subsequent drill breakage could be avoided even when extreme process parameters are chosen. A positive effect was also visible in terms of tool wear.

3 Project description

The previous simple investigations have the disadvantage that the vibration amplitude could not be set exactly and could not be varied either. Therefore in this project a robust and flexible experimental setup is fabricated which allows systematic variation of process parameters. The most important parameters along with its ranges of variation are listed in Table 1.

Figure 3 shows the experimental setup which will be used in future investigations. A piezoelectric transducer is clamped in its vibration node and mounted on an axle. The right end of the axle is plugged into the spindle of the machine tool. Located between transducer and spindle is a contactless energy transmission composed of two copper coils. Each coil is clamped in a ferrite pot core.

The left coil is connected with the transducer and rotates together with the gun drill. The coil on the right is fed by a

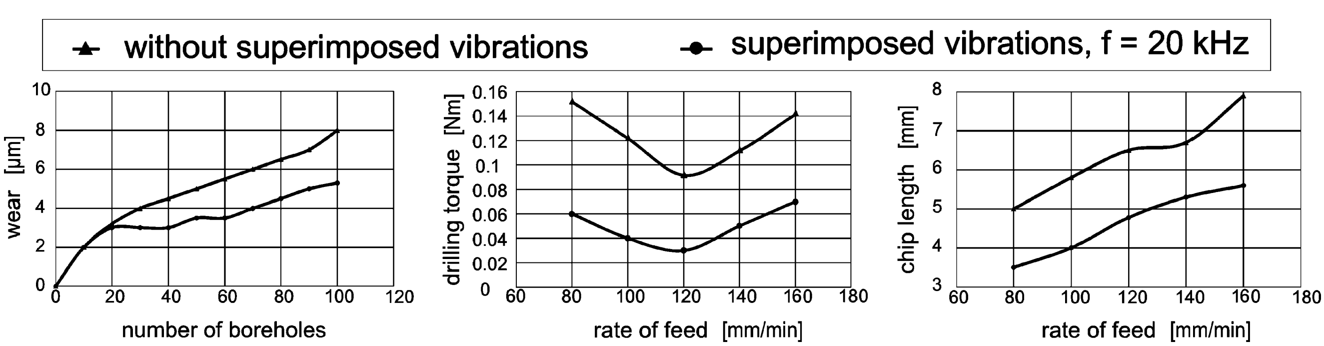


Fig. 2 Effects of superimposed vibrations on wear, drilling torque and chip length

Table 1 Process parameters and range of variation.

Process parameter	Range of variation
Cutting speed	60–160 m/min
Rate of feed	100–400 mm/min
Pressure of lubricant	100–240 bar
Drill diameter	(2.0 and) 5.0 mm
Frequency	20 kHz
Max. vibration amplitude at tool tip	50 µm
Materials	Carbon lead alloy, chromium molybdenum alloy, aluminum alloy
Max. rotation speed	25,500 min^{-1}

high frequency generator, does not rotate and is hold by the housing. The magnetic field transmits the energy through the air gap to the transducer. The transducers' horn has a centre hole for accurately centred booster connection. Besides the transformation of the mechanical vibration amplitude the booster has the function of reception and transmission the cooling lubricant.

4 Design of the piezoelectric transducer

Two different modelling approaches have been pursued for transducer design. For the rough design an analytical rod model was used. This type of model is also called transfer matrix method [2]. The simple rod theory is well adequate for approximation of vibration behaviour if the lateral dimensions of the whole transducer are smaller than one quarter of the wavelength in the frequency of interest. The basic process of the transfer matrix method is: split the transducer into elementary mechanical and piezoelectric rod parts (see Fig. 4), which are homogeneous and geometrically simple, derive the transfer matrix for each rod part and finally concatenate all matrix transfer functions to one whole transfer matrix with respect to series or parallel coupling of the single rod elements.

For each block the analytical model allows the computation of the vibration velocity and force at the right side of the block with respect to vibration velocity and force at its left side. The transfer matrix relation for a mechanical block can be written as

$$\begin{bmatrix} \underline{\widehat{v}}_a \\ \underline{\widehat{F}}_a \end{bmatrix} = \mathbf{A^m} \begin{bmatrix} \underline{\widehat{v}}_e \\ \underline{\widehat{F}}_e \end{bmatrix} \tag{1}$$

Where $\underline{\widehat{v}}_a$ and $\underline{\widehat{F}}_a$ are input velocity and force and $\underline{\widehat{v}}_e$ and $\underline{\widehat{F}}_e$ are the corresponding output quantities, respectively. $\mathbf{A^m}$ is a 2×2 transfer matrix, which is derived from the analytical model:

$$\mathbf{A^m} = \frac{1}{2}\begin{bmatrix} \cos(k_\mathrm{m}L) & \frac{j\Omega}{AEk_\mathrm{m}}\sin(k_\mathrm{m}L) \\ \frac{jAEk_\mathrm{m}}{\Omega}\sin(k_\mathrm{m}L) & \cos(k_\mathrm{m}L) \end{bmatrix} \tag{2}$$

Where j is the imaginary number, Ω is the exciting angular frequency, k_m is the wave number, L and A are length and cross area of the considered block element and E is Young's modulus. For a piezoelectric block the transfer matrix relation can be written as

$$\begin{bmatrix} \underline{\widehat{v}}_a \\ \underline{\widehat{F}}_a \\ \underline{\widehat{I}} \end{bmatrix} = \mathbf{A^p} \begin{bmatrix} \underline{\widehat{v}}_e \\ \underline{\widehat{F}}_e \\ \underline{\widehat{U}} \end{bmatrix} \tag{3}$$

Where $\underline{\widehat{I}}$ and $\underline{\widehat{U}}$ are electric current and voltage. For the 3×3 transfer matrix $\mathbf{A^p}$ see [2]. The whole transfer matrix relation of the transducer can be obtained by connecting transfer matrices of the elementary blocks in terms of interface conditions between two blocks. Creation and solution of the transfer relation can be implemented in a computer algebra program. Further details on this method can be found in [2].

On principle the design parameters can be divided into fixed, variable and vibrational parameters. To the fixed design parameters belong the process parameters, i.e.

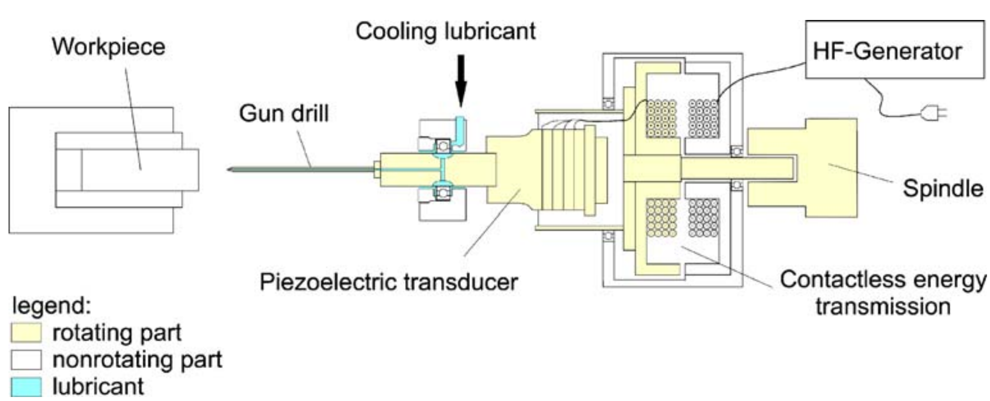


Fig. 3 Experimental setup

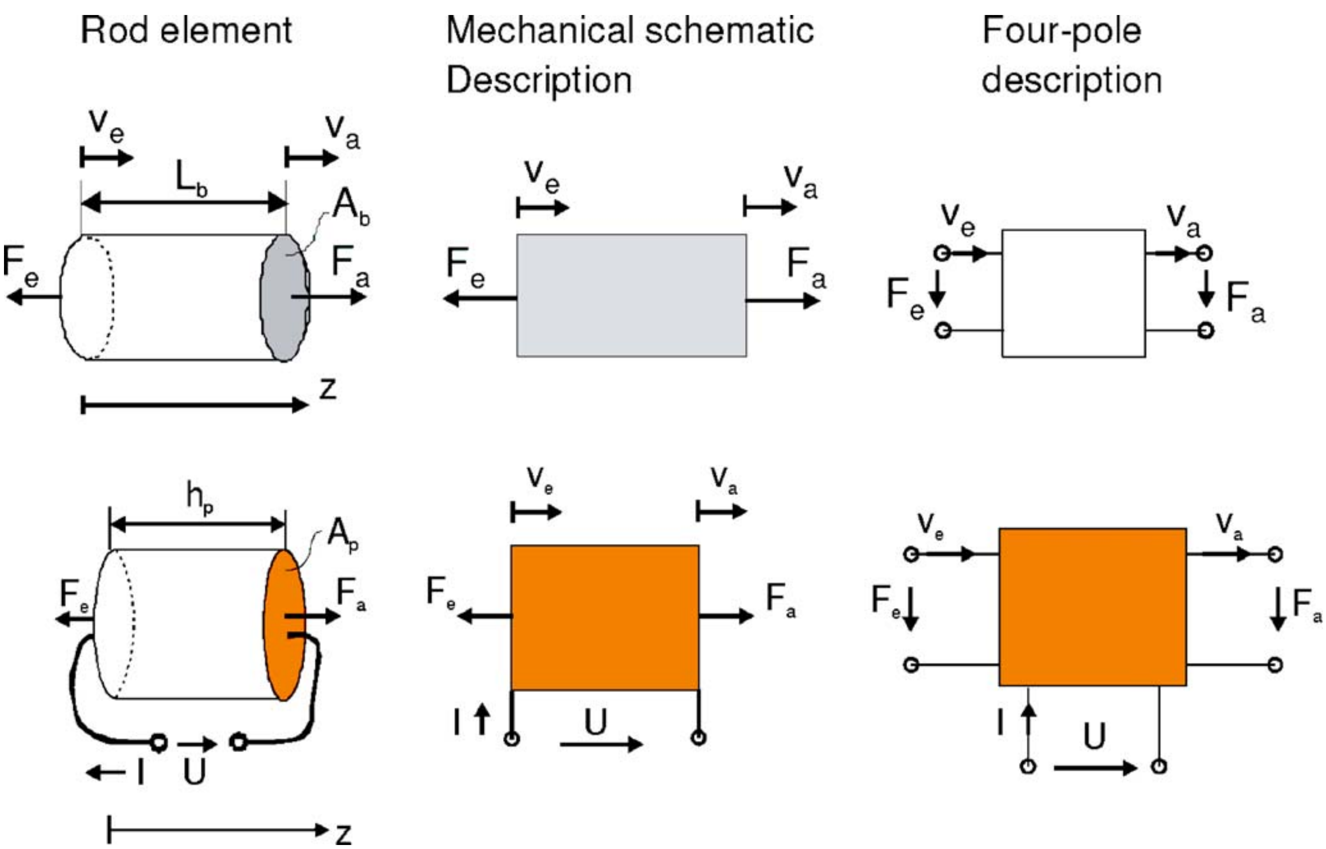


Fig. 4 Mechanical scheme and four-pole description of rod and piezo element [2]

contact force, impedance of tool and workpiece as well as environmental conditions. Variable design parameters include the transducer parameters, i.e. a tuned natural frequency, a nodal position near the mounting and the geometric dimensions. To the vibrational parameters belong the distance between resonance and antiresonance frequency, transformation of vibration amplitudes, maximum strain in the PZT, efficiency and phase minimum.

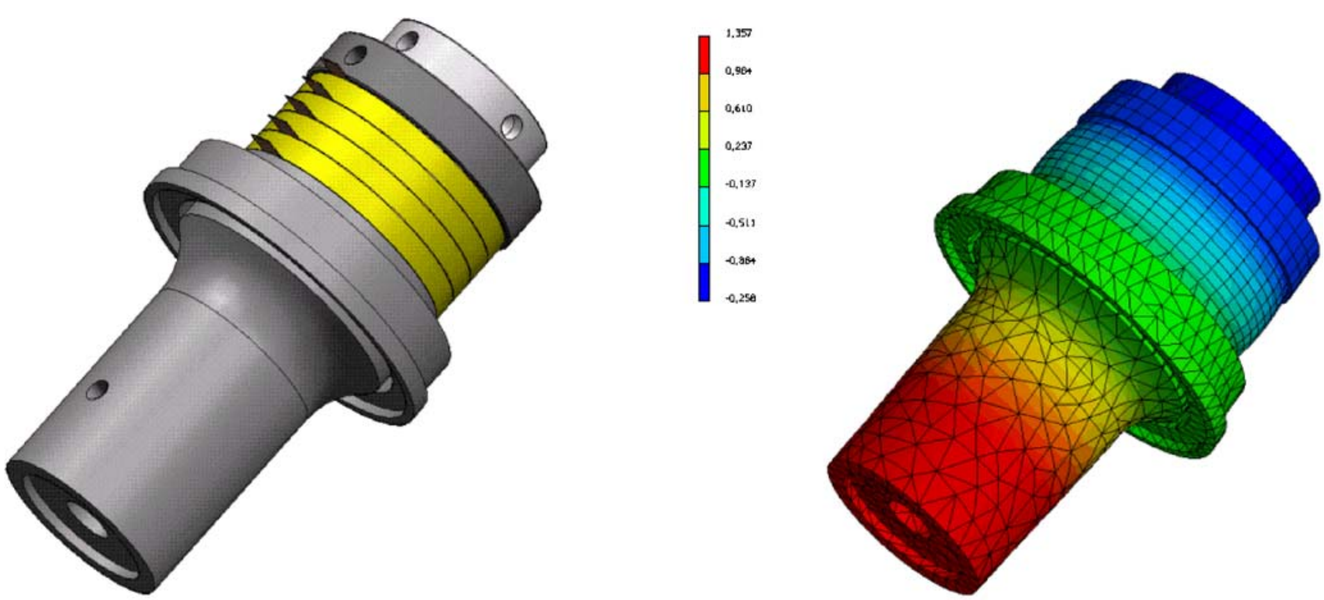


Fig. 5 CAD model and finite element model of the piezoelectric transducer

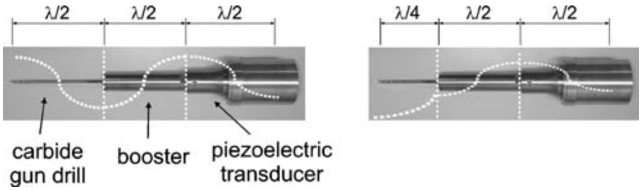


Fig. 6 Schematical illustration of vibration amplitudes along the geometry

The rough transducer design with the matrix transfer method is an iterative process of changing the geometry and solving the corresponding equations until the important design parameters have the desired values. In this specific design a frequency of 20 kHz, a nodal position as close to the mounting as possible and a low amplitude transformation were desired, since the influence of the process needs further investigation in order to determine the optimal transformation. Fundamentally the same design procedure is also possible with the finite element method but one calculation cycle (preprocessing, solution, postprocessing) takes much more time than one cycle with the analytical rod model. According to experience the finite element method gives more accurate results. Hence the rod type model is first used to find a basic geometry and afterwards a modal analysis of this geometry is carried out using Ansys [3]. Finally, only a few subsequent modifications are necessary, for example positional corrections of the bearing. Figure 5 shows the CAD and the finite element model of the designed piezoelectric transducer. The transducer has a length of 118 mm, the substrate material is steel, four hard PIC181 ceramic rings are prestressed by a screw. The actuator is driven in resonance by means of a generator keeping zero phase between current and voltage.

Because of the centre hole in the horn the transducer is a little bit longer than necessary for obtaining the desired resonance frequency of 20 kHz. The effective resonance frequency (19.8 kHz) is therefore lower. The low transformation of the vibration amplitude makes the transducer quite load insensitive.

5 Two different wave length concepts

The vibrational design of longitudinal actuators bases upon a synthesis approach which is well known in ultrasonic technology since a long time. The basic component is a so called λ/2 longitudinal vibrator, since the longitudinal mode shape represents a half of a wavelength. A longer actuator with the same frequency can be achieved by stringing together multiple λ/2 vibrators.

The low amplitude transformation of the transducer makes it necessary to find solutions for higher mechanical amplitudes at the gun drill tip. Since the booster has the function of receiving the cooling lubricant in its vibration node the middle of the booster is unavailable for constructing a transforming step. The achievable amplitude transformation with the designated booster (Fig. 3) is therefore limited. Besides the alternative to arrange a second booster, application of the 3λ/4-concept [4] comes into consideration. The 3λ/4-concept is a not very common approach but it leads to high vibration amplitudes if the λ/4 part is thin compared to the λ/2 parts. Figure 6 shows schematically the vibration amplitudes in axial direction for classical λ/2-concept and for the 3λ/4-concept.

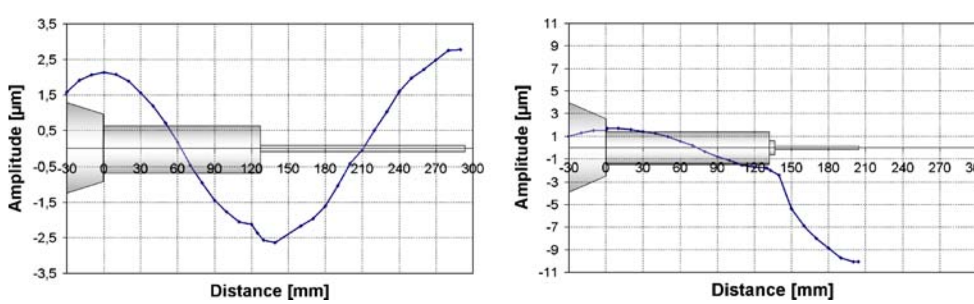
Measurements with a laser vibrometer (Fig. 7) evidence that this wave concept permits very high vibration amplitudes at the tool tip. However, at the junction between booster and carbide drill relatively high strain values occur why the drill is at risk to break at this location. Experiments will show how much amplitude is bearable.

Statements on the load sensitivity of the 3λ/4-concept cannot be made up to now. It is expected that load sensitivity is better than it would be with equivalent transformation with boosters.

6 Conclusion

This paper describes the setup constructed for vibration superimposed drilling in metal materials. The load insensitive piezoelectric transducer is designed with low amplitude transformation in order to stay flexible for adjusting the

Fig. 7 Waveform measurements of the two different concepts



desired amplitude with boosters or with the described 3λ/4-concept. The energy is transmitted contactless into the rotating transducer. The modified electrical behaviour can be adjusted via two capacities, one arranged in series and one in parallel. Right now the setup is near completion. Experimental results will be published in near future.

Acknowledgements Thanks belong to the German Research Council (DFG) for funding this research project as grant no. WA 564/10-1.

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