Ultrasonic deep hole drilling in electrolytic copper ECu 57

U. Heisel (1) a,*, J. Wallaschek b, R. Eisseler a, C. Potthast c

a Institute for Machine Tools, University of Stuttgart, Stuttgart, Germany
b Institute of Dynamics and Vibration Research, Leibniz University, Hannover, Germany
c Institute for Mechatronics and Dynamics, University of Paderborn, Paderborn, Germany

A R T I C L E   I N F O
Keywords:
Drilling
Ultrasonic
Deep hole

A B S T R A C T
At present the machining of highly ductile electrolytic copper ECu 57 with gun drills is carried out at very low feed values, as the material tends to form very long and unfavourable chips. In addition, high frictional forces on the guide rails cause high torsional strain on the gun drill. This paper first reports on the results of ultrasonically assisted deep hole drilling in ECu 57 with tools of 5 mm diameter. The actuator system for exciting axial vibrations in the ultrasonic range is described and experimental results which were obtained from cutting tests are reported. Particular emphasis is put on the improvements compared with the conventional drilling technology without superimposed vibrations. The effect of different input amplitudes is investigated in detail. The performance criteria are drilling moment, surface quality, chip form as well as the surface zone. By optimising the vibration amplitude, cutting speed and feed, the machining result was improved compared with conventional machining, and at the same time the stability of the machining process was simultaneously increased.

© 2008 CIRP.

1. Introduction

Deep hole drilling does not only allow to produce holes with very large drilling depth/diameter ratios of up to \( l/d = 250 \) [1], but is also used if high surface qualities are to be attained without subsequent precision machining. The prerequisite for a stable deep-hole drilling process is, however, a continuous chip removal inside the chip flute of the tool. This is achieved by delivering cooling lubricant under high pressure with up to \( p_{\text{max}} = 2.5 \times 10^5 \) Pa through an inner channel to the cutting region. Given the tool diameter, very small wall thicknesses in the range of 0.1–0.2 mm result due to the large channel cross-sections, making the gun drilling tool extremely susceptible to breakage.

Electrolytic copper (ECu) material has a high electrical and thermal conductivity. Hence it is used for highly conductive electrical products as well as for small high-performance heat exchangers in the field of chemistry. In both cases, however, particularly in the production of heat exchangers, a large number of holes with smallest diameters must be drilled into a component. Electrolytic copper tends to form long ribbon and snarled chips due to its characteristic high elongation of \( A = 40\% \) and a tensile strength of \( R_m = 300 \) N/mm\(^2\). Hence there is a high risk of unstable processes due to the more difficult chip removal. In consequence, insufficient surface qualities due to rubbing chips or even tool breakage must be expected. For this reason, drill holes with large \( l/d \) ratio are produced at greatly reduced feed values.

It is known from previous work that the chip length in deep hole drilling of martensitic steel can be influenced by superimposing vibrations in the frequency range between 0 and 1000 Hz [2]. In contrast to the attempts at minimising or avoiding vibrations in drilling operations [3], the input of vibrations into the machining process is deliberate and defined here. The advantages of these so-called hybrid processes were also described in the work dealing with the ultrasonic drilling and deep hole drilling of metals, not only hard and/or brittle materials such as, for example, ceramics or glass [4] but also of steel materials [5]. Apart from influencing chip length, the input of vibrations was also described as the possibility to reduce the process parameters of feed force and drilling moment. Vibrations primarily in the longitudinal direction of the drilling tool were generated with the piezoelectric actuators used here.

2. Design of the piezoelectric transducer

The development of an ultrasonic actuator for deep hole drilling is described here. This actuator was built as a prototype and designed in two steps, building on each other. At first, a basic design of the actuator was carried out by means of analytical approximate equations describing the substitute model for the longitudinal vibrations of a rod. Then an optimisation with regard to the realisable vibration amplitude \( \hat{u} \) was conducted by means of an FEM model, by which design details can be described as well.

2.1. Analytical design of the piezoelectric actuator

For the basic design of the ultrasonic actuator, an analytical rod model was used, in which the vibration behaviour of the system is described by means of the transfer matrix method [6]. The rod model is well suited to determine approximately the vibration behaviour as long as the lateral dimensions of the whole transducer are less than a quarter-wavelength of the frequency of interest.
The basic idea of the transfer matrix method is to split the transducer into elementary mechanical and piezoelectric rod parts, each of which are geometrically simple in themselves. The corresponding transfer matrices are derived for each of the rod parts and finally combined into an overall transfer matrix, taking the series and parallel coupling of the individual rod elements into account (see Fig. 1).

Assuming harmonic vibrations, the analytical model allows description correlation of the cutting parameters for each block. However, only the amplitudes in steady state condition are considered here. Hence the transfer matrix for a “passive” rod can be described as follows

\[
\begin{bmatrix}
\hat{v}_e \\
\hat{F}_e \\
\hat{l}
\end{bmatrix} = A^m
\begin{bmatrix}
\hat{v}_a \\
\hat{F}_a \\
\hat{l}
\end{bmatrix}
\]  

(1)

Here \( \hat{v}_a \) and \( \hat{F}_a \) represent input velocity and force, e.g. at the left end, whereas \( \hat{v}_e \) and \( \hat{F}_e \) are the corresponding output variables. \( A^m \) is a \( 2 \times 2 \) transformation matrix, resulting in

\[
A^m = \frac{1}{2} \begin{bmatrix}
\cos(k_mL) & \frac{j\Omega}{AEk_m} \sin(k_mL) \\
\frac{jAEk_m}{\Omega} \sin(k_mL) & \cos(k_mL)
\end{bmatrix}
\]

(2)

for a rod with constant cross-section. Here \( j \) is the imaginary unit, \( \Omega \) is the angular frequency of the excitation, and \( k_m \) is the wave number. \( L \) and \( A \) are the length and the cross-section of the rod element examined, and \( E \) is the modulus of elasticity. For an “active” piezoelectric block the transformation matrix results as follows

\[
\begin{bmatrix}
\hat{v}_e \\
\hat{F}_e \\
\hat{l}
\end{bmatrix} = A^p
\begin{bmatrix}
\hat{v}_a \\
\hat{F}_a \\
\hat{l}
\end{bmatrix}
\]

(3)

where \( l \) and \( U \) are electric current and applied voltage. The structure of the \( 3 \times 3 \) matrix \( A^p \) and other details of the transfer matrix method are described in detail in [6].

The overall transfer matrix of the transducer is produced by connecting the transfer matrices of the elementary blocks, taking into account each of the interface conditions between two blocks. The creation and solution of the transformation relations can be carried out with computer algebra programs [6].

The transducer and its operating conditions are described by means of definitely given parameters such as, for example, the process parameters of excitation frequency, contact pressure, etc. as well as the design parameters such as, e.g. the impedance of tool and workpiece. The design parameters depend on the tuning of the natural frequency and natural mode of the system or the material parameters and geometric dimensions of the actuator [7]. Concerning vibration, important parameters include the separation between resonant and antiresonant frequency, the transformation of the vibration amplitudes as well as the efficiency and position of the phase minimum.

The basic design of the transducer with the transfer matrix method was carried out in an iterative process. In this process the geometry of the system was gradually modified until the most important design objectives were reached. In this case the aim was to achieve a frequency of 20 kHz and a low amplitude transmission. The latter requirement followed from the fact that reactions of the machining process to the vibration characteristic should be minor.

The finite element method provides more accurate results, however the calculation is more time-consuming than using the rod model. Hence the basic geometry was first determined with the rod model here, and then it was optimised with the FEM. Only few modifications in detail had to be made here such as, for example, the final positioning of the bearing points. The transducer is 118 mm long and made of steel. Moreover, four rings of PIC181, a so-called “hard” piezoceramics, are integrated and prestressed by a screw. The actuator is driven in resonance by a generator, readjusting a phase shift of 0° between current and voltage flow.

2.2. Increase in vibration amplitude

The vibration dimensioning of ultrasonic tools is carried out by means of the so-called half-wave synthesis. In this process the smallest unit is a so-called \( \lambda/2 \) longitudinal vibrator for systems conducting vibrations in the longitudinal direction. In this unit the mode form is represented by half a wavelength, and the system is designed for a given resonant frequency. Then longer ultrasonic tools can be obtained by stringing together several \( \lambda/2 \) vibrators, which are all tuned to the same resonant frequency. In this way it is achieved that the total system is in resonance at the given frequency as well. The geometry of the drilling tool was optimised in order to attain high mechanical amplitudes at the gun drill point, despite the existing low transformation of the transducer. The easiest way would be to carry out the desired amplitude transformation via a cross-sectional junction in the middle of the booster. Other options would be to add a second booster or to use a design according to the \( 5\lambda/4 \) concept [8]. Fig. 2 shows schematically the vibration amplitudes in axial direction for the \( \lambda/2 \) 2 concept and the \( 5\lambda/4 \) concept [9].

Measurements with a laser vibrometer (Fig. 3) showed that very high amplitudes at the tool tip are reached with the \( 5\lambda/4 \) concept. These high amplitudes, however, involve high loads on the junction of booster and carbide drill. In the cutting tests conducted, the vibration input led to no tool breakage.

3. Cutting tests

Using the actuator described above (see Fig. 4), cutting tests were carried out on ECU 57 and analysed. The quasi-static drilling...
moment $M_z$, surface quality, chip form, burr formation and the hardening of the drill hole’s surface zone were used as criteria. The details of the tools used are presented in Table 1.

The experimental tests were conducted at the frequency of $f_{\text{act}} = 20$ kHz, established by the actuator, with varying vibration amplitudes $\hat{u}$ as well as varying feed values $f$. The cutting speed was constantly fixed at $v_c = 40$ m/min. The comparatively low value of the cutting speed is conditioned by the prototypical construction of the actuator.

3.1. Quasi-static drilling moment

In Fig. 5 the quasi-static drilling moment $M_z$ depending on feed is presented for different no-load amplitudes $\hat{u}$. In the case of conventional drilling without vibration input ($\hat{u} = 0 \mu$m), the expected increase in drilling moment up to $M_z = 0.52$ N cm at $f = 16$ $\mu$m shows, depending on feed. The curve can be considered as quasi-linear in the feed range examined. If ultrasound is used, the curves are far less progressive and strongly depend on the set no-load amplitude $\hat{u}$. Especially at $\hat{u} = 6.7$ $\mu$m, there is nearly no correlation between feed force $F_z$ and feed $f$ in the feed range examined. The curves are almost identical up to $f = 14$ $\mu$m.

Moreover, the curves for $\hat{u} = 6.7$ $\mu$m show areas in which the gradient of the curve changes. This point is at $f = 8$ $\mu$m for $\hat{u} = 4.1$ $\mu$m and at $f = 14$ $\mu$m for $\hat{u} = 6.7$ $\mu$m. These areas represent the lowest feed values at which the cutting edge just exits the workpiece in the course of a vibration period.

3.2. Quality of surface

The centre line average height $R_a$ was used to assess the attainable surface quality. Up to the feed of $f = 8$ $\mu$m, the courses of $R_a$ presented in Fig. 6, point to a clear improvement in surface quality due to the input of ultrasonic vibration. The measurements were taken in feed direction using the profile method with a cutoff length of $\lambda = 0.8$ mm and a measured length of $5\lambda = 4.0$ mm.

From a feed of $f > 8$ $\mu$m up, the conditions could not have been definitely clarified until now. The input of ultrasound has a clear influence on the shaping of the surface structure, as presented exemplarily for a feed of $f = 16$ $\mu$m in Fig. 7. Fig. 7(a) shows the kinematic roughness caused by the set feed in conventional drilling ($\hat{u} = 0 \mu$m). Fig. 7(b) depicts the surface produced with the no-load amplitude of $\hat{u} = 11.7$ $\mu$m, showing not only an existing basic waviness but also a comparatively isotropic structure orientation. The basic waviness here varies with the relation as well as the phase shift between the actuator frequency $f_{\text{act}}$ and the angular frequency $v$ of the tool. The basic waviness here varies with the relation as well as the phase shift between the actuator frequency $f_{\text{act}}$ and the angular frequency $v$ of the tool. Due to the relative motion between set feed and vibration amplitude $\hat{u}$, the tool marks

![Fig. 3. Vibration modes measured (axial direction) for 5x4 concept.](image1)

![Fig. 4. Prototypical actuator for ultrasonic deep hole drilling.](image2)

![Fig. 5. Quasi-static drilling moment $M_z$ depending on feed $f$ and no-load amplitude $\hat{u}$.](image3)

![Fig. 6. Centre line average height $R_a$ depending on feed $f$ and no-load amplitude $\hat{u}$.](image4)

![Fig. 7. Surface structure generated without (a) and with (b) ultrasound.](image5)

![Fig. 8. Chip forms in conventional (a) and ultrasonic (b) machining.](image6)
are covered up levelling out the profile maxima and minima by means of deformed workpiece material.

3.3. Chip form

Samples were taken of the chips and evaluated in order to compare conventional with ultrasonic machining. Fig. 8 shows the chips forming at the set feed of \( f = 16 \, \text{m}\). As depicted in Fig. 8(a), long ribbon chips with comparatively high chip thickness ratio were produced in conventional machining. When ultrasound is used (Fig. 8(b)), clearly shorter helical chips arise, which have a lower chip thickness ratio. These chips can be better removed from the drill hole and hence contribute to a higher process stability.

3.4. Influence on surface zone

Using a nanoindenter, the effect of how the input of ultrasound influences the properties of the workpiece material in the surface zone could be shown. The measurements were carried out on conventionally machined drill holes as well as on holes produced with ultrasound and a no-load amplitude of \( \bar{u} = 11.7 \, \text{m}\). The feed was set at \( f = 16 \, \text{m}\) in both cases. The test force was increased up to \( F_{\text{max}} = 5 \, \text{N} \) and kept there for three seconds before unloading. A diamond pyramid with a 120° tip angle was used as indenter. Fig. 9 illustrates the loading and unloading curves of the nanoindenter measurement, leading to two findings.

On the one hand, the residual deformation is lower for ultrasonically machined surfaces, indicating a higher density of the material. On the other hand, these differences can be observed up to a penetration depth of about 2 \( \mu\text{m}\).

4. Summary

As described above, a piezoelectric actuator which can be used for ultrasonic deep hole drilling into metal materials was developed. The piezoelectric transducer was designed with regard to the low amplitude transmission, to guarantee a system that is as adaptable as possible and insensitive to loads in later operation. Subsequent cutting tests showed that the process parameters of drilling moment and feed force can be favourably influenced by means of ultrasound. In addition, it could be proved that, compared with conventional machining, a higher surface quality can be achieved in the case of an optimised combination between the set feed and no-load amplitude of the actuator. Due to a simultaneously favourable chip form and length, a higher process stability can be guaranteed as well. Examinations of the surface zone, which were additionally carried out, indicate that vibration superposition influences the material properties of the workpiece.

Acknowledgement

The research was supported by the German Research Foundation (DFG), HE 1656/75-1, WA 564/10-1.

References