Kinematic analysis and process stability of ultrasonic-assisted drilling

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Abstract

Regarding drilling, ultrasonic-assistance enables various potentials such as less tool wear, enhanced chip breaking and burr reduction. Although there are many technological studies verifying these advantages, no theory for process behaviour, design and parameter evaluation is available. Thus, this paper presents a kinematic analysis of the interaction between tool and workpiece to contribute to overall process understanding. Specific process scenarios are classified and characteristic parameters for the evaluation and design of ultrasonic-assisted drilling are determined. In addition, experimental investigations based on the developed process model are carried out analysing chip shape, bore surface and process stability acquired by acoustic measurements. The kinematic analysis shows the classification of ultrasonic-assisted drilling according to continuous and intermitted cutting conditions. In addition, the superposition of ultrasonic vibrations causes a modulation of uncut chip thickness related to the ratio of ultrasonic frequency and spindle speed. In general, experimental results show that ultrasonic-assisted drilling is leading to shorter chips. While using parameters for intermitted cutting conditions needle chips occur. At the same time, intermitted cutting conditions induce process instabilities identified using the acoustic measurement approach.

Keywords Ultrasonic · Hybrid machining · Drilling · Machining · In-process measurement

1 Introduction

Due to increasing demands on manufacturing processes aiming for higher resource and energy efficiency, minimization of production costs and time combined with unchanged or even better quality, it is necessary to shift limits of conventional machining processes. The approach of hybrid machining is a suitable method that enables high-performance cutting to address these challenges [1]. In this context, vibration-assisted machining (VAM) uses additional energy in terms of vibrations to realize a hybrid process [2]. Ultrasonic-assisted machining (UAM) operates with high frequencies above the human threshold of hearing of approximately 20 kHz. Since the early beginnings in the 1960's [3, 4], ultrasonic assistance was studied covering a wide range of machining processes [2, 5].

In general, UAM provides lower process forces, increased tool life and process stability, better chip breaking, avoidance

of burrs and build-up edges as well as reduced surface roughness or higher removal rates [5–8]. Applying vibrations to the process zone directly affects the chip formation and contact between tool and workpiece via kinematic, tribological and material effects. Basic mechanisms and performance depend on the application conditions of the ultrasonic assistance such as the primary machining process, workpiece material and direction of vibration. Therefore, considering these conditions is essential for investigating kinematics, effects and process design of ultrasonic-assisted processes. The following two examples illustrate the differences within UAM. Concerning ultrasonic-assisted turning, vibration in cutting direction including the kinematic mechanism is well studied [9–12]. The vibration leads to a modulation of cutting speed, and if the process setup is appropriate, an interrupted cutting process takes place. While the tool is in complete contact with the workpiece, the material load reaches the yield strength and chip formation occurs. During the period of interruption, process forces break down and the tool is unloaded. As a result, the periodic characteristic leads to a decrease of mean forces by up to 75% [5] and hence to higher tool life and to improved surface roughness [13, 14]. Other effects dominate using UAM for brittle materials. In peripheral grinding, vibrations are located in the direction of feed or depth of cut [15]. Ultrasound induces the formation of micro cracks in the brittle

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material [16]. In combination with the cleaning effect of the grinding disk, ultrasonic-assisted grinding leads to a significant potential for enhanced removal rates of up to 236% [15]. Although these processes have been researched for years, not all characteristics and effects of the ultrasonic-assistance in machining are known and for numerous applications the process understanding is limited [5, 6, 17, 18].

Regarding drilling processes, especially deep hole drilling, evacuation of chips is critical for process reliability and performance. Inappropriate chip formation leads to high torque, higher surface roughness, tool wear and breakage. The approach of ultrasonic assistance directly influences the chip formation and produces improved chip breaking behaviour. Neugebauer and Stoll [19] proved the improved chip breaking caused by ultrasonic assistance for drilling of 44MnSiVS6. In [20] Neugebauer et al. as well as Lofti and Amini in [21] investigated the kinematic mechanism via FEM simulation. Their research has shown that the modulation of chip thickness and a decreased radius of chip curvature are responsible for improved chip breaking behaviour. Moreover, Heisel et al. [22] and Eisseler [23] found that ultrasonic assistance in deep hole drilling reduces chip jam significantly and results in lower torque. The decreased mechanical tool load diminishes the risk of tool breakage. Baghlani et al. [24] showed that this enables deep hole drilling with sufficient process reliability even for super alloys such as Inconel 738. The research of Makhdum et al. [25, 26] highlighted the potential of UAD for decreased delamination in carbon fibre-reinforced plastics. Other works, for example, of Stoll et al. [27], Gupta et al. [28] and Sanda et al. [29], confirmed this capability. Furthermore, the potential to decrease burr formation on the hole exit is reported as a main advantage of UAD. Takeyama and Kato [30] firstly documented the burr reduction. While drilling aluminium with ultrasonic assistance, they were able to reduce burr height by up to 80%. The research of Chang and Bone [31] as well as Babitsky et al. [32] confirmed burr reduction in aluminium alloys. In contrast, for UAD of C45E Heisel et al. [33] could not verify a change of burr formation. He suspected the low vibration amplitude to be responsible. Further research investigated UAD of Ti6Al4V. Sanda et al. [29] realized a burr height reduction of approx. 20% and Li et al. [34] conversely of approx. 80–90%. The decrease of process forces often is referred to as the main benefit of UAM. However, compared to machining processes with modulated cutting velocity, the ability for minimizing thrust forces via UAD's kinematic mechanism of feed modulation is moderate. Nevertheless, prior research shows a wide range of results. Considering aluminium alloys, the level of force reduction is similar. Li et al. [35] obtained a reduction of approx. 28% (EN AW-7075) and Paktitad and Amini [36] of approx. 37% (EN AW-7075). Chang and Bone [37] developed a thrust force model based on the fundamental process kinematics. Depending on the

process parameters, the model as well as the experimental investigations showed a moderate thrust force reduction of max. 16%. In contrast, Baghlani et al. [38] obtained a thrust force reduction higher than 40% (Inconel 738), Takeyama and Kato [30] (aluminium) as well as Makhdum et al. [26] (carbon fibre-reinforced plastics) even higher than 80%. While the research of Moghaddas et al. [39] reached a thrust force reduction of approx. 42% for steel 1.6511, Heisel et al. [33] measured increased thrust forces of up to 10 % for steel 1.1191. It is obvious that further reasons contribute to this widely spread values. Reasons could be the avoidance of build-up edges, reduced friction, changes in material behaviour like the Blaha effect [40], changed effective rake angles or a divergent shape of vibration.

Overall, parameter studies dominate the state of the art regarding UAD with defined cutting edge. For specific conditions, the experimental investigations analyse the potentials compared to conventional drilling. Moreover, the state of the art reveals some important mechanisms but a theory for setting up process and vibration parameters is missing. Analytic models of the process kinematics can explain fundamental effects and contribute to a theory for process design. Regarding basic kinematics of the drilling process interacting with the longitudinal vibration, UAD has similarities with low-frequency vibration-assisted drilling processes. Usually, they provide low-frequency vibrations below 1000 Hz combined with high amplitudes to improve chip breaking through the periodical change of chip thickness via a non-resonant system. Several research activities focus on the kinematics of these processes. Wang et al. [41] developed a kinematic model of the cutting-edge trajectory in low-frequency vibration-assisted drilling. Based on this, they calculated uncut chip thickness, thrust force and torque. In further research, Wang et al. [42, 43] investigated the relationship of amplitude and feed as well as of frequency and rotation speed. They introduced factors to describe the influence of vibration parameters on process properties and performed experimental investigations in fibre-reinforced plastics. For this purpose, the researchers used a vibration system with included piezoelectric actuators limited to a maximum amplitude of 35 μm . Years later, Pecat and Meyer [44] investigated low-frequency vibration-assisted drilling with a tool vibration system which provided amplitude of maximum 0.2 mm thru a special bearing system inside the tool holder. In addition, they developed a kinematic process model to describe continuous and intermitted cutting conditions aiming to identify suitable cutting parameters. In [45] they showed that low-frequency vibration-assisted drilling with intermitted cutting conditions has a positive effect on tool wear propagation in carbon fibre-reinforced plastic and titanium alloy stack material. Ladonne et al. [46] and Le Dref et al. [47] carried out further investigations about process kinematics and modelling of low-

frequency vibration-assisted drilling. Regarding UAD, Neugebauer and Stoll [19] showed the tool path including the ultrasonic motion in feed direction as well as a chart for the periodical change of the effective angles. Lee et al. [48] developed a kinematic model to calculate the uncut chip thickness and the kinematically determined chip shape. Le et al. verified the results with a comparison of chip shape and hole wall structure with experimental tests of UAD in aluminium alloy EN AW-6061, applied through a workpiece vibration system with fixed frequency. Chang and Bone [37] also based the kinematic model on a vibration workpiece fixture with fixed frequency. The model included the vibration-assisted motion of the cutting edge, uncut chip thickness and intermittent cutting conditions. Based on the kinematic model, Chang and Bone developed a thrust force model considering strain rate dependency and plowing effect. Compared to the experimental results in EN AW-7075, the results reached a suitable accuracy with an error of maximum 10%. In [49] Chang and Bone extended the thrust force model with a burr model to calculate burr height. Li et al. [34] investigated UAD with a vibration tool system in Ti6Al4V. To analyse process kinematics of the cutting edge, Li et al. used a similar model as Chang and Lee. Additionally, Li et al. investigated the behaviour of the chisel edge within conditions for intermittent cutting and the plowing effect. Current models for UAD are able to describe the process kinematics, thrust force or even burr height for given parameters within a fixed frequency. Nevertheless, fundamental mechanisms especially the relations between feed and amplitude as well as rotation speed and ultrasonic frequency, including the interaction between conventional and vibration parameters to set up suitable

process properties, has not been investigated in detail. Aiming to contribute to a theory for process design and evaluation of UAD, it is important to consider a changing vibration frequency because of the resonance control of the ultrasonic system.

This paper aims at generating a better understanding of the behaviour of ultrasonic-assisted drilling (UAD) with defined cutting edge using a resonant system to generate vibrations in feed direction. Thus, the paper analyses the fundamental kinematics of UAD as well as secondary effects caused by the ultrasonic assistance. General process scenarios are classified and key aspects for designing UAD processes are discussed. Therefore, the paper focusses on the interaction between conventional and vibration parameters. Moreover, acoustic measurements show the ability to evaluate process characteristics in-process.

2 Kinematic process model

The kinematic process model is the basic principle to investigate effects of UAD. Figure 1 shows the fundamental process kinematics and Fig. 2 illustrates the orthogonal tool plan. The drilling tool rotates with rotary speed n creating cutting speed v_c . The feed direction with feed f and feed velocity v_f is superimposed by the ultrasonic vibration including the velocity $v_{z, US}$ characterized by the ultrasonic frequency f_{US} , the angular frequency ω_{US} and the amplitude A . Thus, the longitudinal ultrasonic vibration modulates the uncut chip thickness. In this context, the term modulation defines a periodical change of the former constant value. To present the kinematic

Fig. 1 Fundamental process kinematics of UAD

Fig. 2 Orthogonal tool plan of UAD

mechanisms of UAD, the model focuses the cutting-edge corner neglecting the cutting edge radius. Regarding the cutting direction, common equations remain valid.

$$v_c = \pi \cdot D \cdot n \quad (1)$$

$$v_f = n \cdot f \quad (2)$$

The ultrasonic vibration shows the behaviour of harmonic equations with z_{US} for the path coordinate, $v_{z, US}$ for the velocity and $a_{z, US}$ for the acceleration. Moreover, at starting time t_0 the angle φ_0 is zero.

$$z_{US}(t) = A \cdot \sin(\omega_{US} \cdot t + \varphi_0) \quad (3)$$

$$v_{z,US}(t) = A \cdot \omega_{US} \cdot \cos(\omega_{US} \cdot t + \varphi_0) \quad (4)$$

$$a_{z,US}(t) = -A \cdot \omega_{US}^2 \cdot \sin(\omega_{US} \cdot t + \varphi_0) \quad (5)$$

In feed direction, vibration and feed velocity superimpose and generate the process velocity v_z .

$$v_z(t) = v_f + v_{z,US}(t) = v_f + A \cdot \omega_{US} \cdot \cos(\omega_{US} \cdot t + \varphi_0) \quad (6)$$

Hence, the path of the cutting tool edge in the feed direction shows the following equation combining ultrasonic path z_{US} and conventional feed path z_f .

$$z(t) = z_f(t) + z_{US}(t) = v_f \cdot t + A \cdot \sin(\omega_{US} \cdot t + \varphi_0) \quad (7)$$

When investigating effects of UAD, it is favourable to describe the path coordinate z according to the cumulative angle of the tool rotation $\varphi_{D, cum}$ or the angle of the cutting-edge orientation φ_D within N_D for the number of complete tool rotations (positive integer).

$$N_D(t) \in \mathbb{N} = \lfloor n \cdot t \rfloor \quad (8)$$

$$\varphi_{D, cum}(t) = 2 \cdot \pi \cdot n \cdot t = 2 \cdot \pi \cdot N_D + \varphi_D \quad (9)$$

$$z(\varphi_{D, cum}) = v_f \cdot \frac{\varphi_{D, cum}}{2 \cdot \pi \cdot n} + A \cdot \sin\left(\omega_{US} \cdot \frac{\varphi_{D, cum}}{2 \cdot \pi \cdot n} + \varphi_0\right) \quad (10)$$

$$z(\varphi_D, N_D) = v_f \cdot \frac{\varphi_D + 2 \cdot \pi \cdot N_D}{2 \cdot \pi \cdot n} + A \cdot \sin\left(\omega_{US} \cdot \frac{\varphi_D + 2 \cdot \pi \cdot N_D}{2 \cdot \pi \cdot n} + \varphi_0\right) \quad (11)$$

Figure 3 shows the tool path related to the angle of the cutting edge for an exemplary parameter setup. Depending on the type of the drilling tool and the number of cutting edges Z , multiple paths interact in parallel.

Unlike in conventional drilling, feed and uncut chip thickness are not constant values in UAD. In addition, cutting generates a wavy surface related to the ultrasonic vibration. Thus, cutting conditions, e.g. uncut chip thickness, depend on the surface structure and the UAD tool path of the cutting edge. The relevant surface structure is generated by the previous rotation for single cutting-edge tools and by the previous cutting edge for tools with two or more cutting edges respectively. The kinematic process model is based on the assumption that the surface is reproduced exactly like the kinematics of the cutting edge. Due to the similar path and the neglected cutting edge radius, the structure shows a sinusoidal character within a shift in phase and z-coordinate towards tool path of the actual cutting edge. While z-coordinate shift is equal to conventional feed per tooth f_z , UAD needs new parameters for the phase shift $\varphi_{US, D}$, the dynamic feed per tooth $f_{z, dyn}$ and the dynamic uncut chip thickness h_{dyn} . Figure 4 shows the basic mechanism and the parameters for the cutting edge path with rotation number N_D , surface structure generated from $N_D - 1/Z$ and the conventional path. Equations (12), (13), and (14) determine dynamic feed per tooth considering the number of cutting edges Z .

$$f_{z, dyn}(t) = z(t) - z\left(t - \frac{Z}{n}\right) \quad (12)$$

Fig. 3 Cutting-edge path for ultrasonic-assisted drilling

$$f_{z,dyn}(\varphi_{D,cum}) = z(\varphi_{D,cum}) - z\left(\varphi_{D,cum} - \frac{2 \cdot \pi}{Z}\right) \quad (13)$$

$$f_{z,dyn}(\varphi_D) = z(\varphi_D) - z\left(\varphi_D - \frac{2 \cdot \pi}{Z}\right) \quad (14)$$

The uncut chip thickness shows a similar behaviour considering the tool point angle σ . Negative values of $f_{z,dyn}$ define points of interrupted cutting where no chip formation takes place. Therefore, for all negative values of $f_{z,dyn}$, the uncut

Fig. 4 Mechanism and parameters of UAD

chip thickness h_{dyn} is zero. Moreover, in this case, the generated surface differs from the sinusoidal shape. Equation (15) considers this effect for the next passage of a cutting edge.

$$h_{dyn}(t) = \begin{cases} 0 & \text{if } f_{z,dyn}(t) < 0 \\ \left(f_{z,dyn}(t) + f_{z,dyn}\left(t - \frac{1}{n \cdot Z}\right) \right) \cdot \sin\left(\frac{\sigma}{2}\right) & \text{if } f_{z,dyn}\left(t - \frac{1}{n \cdot Z}\right) < 0 \\ f_{z,dyn}(t) \cdot \sin\left(\frac{\sigma}{2}\right) & \text{otherwise} \end{cases} \quad (15)$$

Based on Eqs. (13) and (14), the characteristic of dynamic feed per tooth is similar for each tool rotation. Hence, phase shift $\varphi_{US,D}$ is a constant value for each parameter setup. With the number of complete ultrasonic-vibration periods per tool rotation N_{US} (positive integer) and the adapted number for Z^{-1} tool rotations $N_{Z,US}$ (positive integer), meaning the complete ultrasonic vibrations to the next cutting edge, the following equation determines phase shift in ultrasonic-assisted drilling.

$$N_{Z,US} \in \mathbb{N} = \left\lfloor \frac{f_{US}}{Z \cdot n} \right\rfloor \quad (16)$$

$$\varphi_{US,D} = \left(\frac{f_{US}}{Z \cdot n} N_{Z,US} \right) \cdot 2 \cdot \pi \quad (17)$$

Phase shift directly affects dynamic feed per tooth.

$$f_{z,dyn}(t) = A \cdot \sin(\omega_{US} \cdot t + \varphi_0) - A \cdot \sin(\omega_{US} \cdot t + \varphi_0 - \varphi_{US,D}) + f_z \quad (18)$$

Investigating this behaviour, characteristic configurations occur. Phase shift of 0° leads to a constant dynamic feed per tooth similar to the conventional feed per tooth. In this case, the modulation effect disappears. All other values of phase shift lead to modulated feed with a maximum modulation

effect at 180° . Figure 5 shows the path and dynamic feed per tooth for the characteristic values of the phase shift.

Moreover, the high velocity of the ultrasonic vibration changes the speed ratio especially the effective speed. Due to the ultrasonic frequency, the vibration velocity is higher than feed velocity. Hence, regarding the feed direction, a real backward motion of the tool takes place (Fig. 6). This affects the value of the effective speed and the orientation expressed by the effective direction angle according to Eqs. (19) and (20).

$$v_e(t) = \sqrt{v_z(t)^2 + v_c^2} = \sqrt{(v_f + v_{z,US}(t))^2 + v_c^2} \quad (19)$$

$$\eta(t) = \tan^{-1}\left(\frac{v_z(t)}{v_c}\right) = \tan^{-1}\left(\frac{v_f + v_{z,US}(t)}{v_c}\right) \quad (20)$$

Similar to the dynamic behaviour of feed as well as uncut chip thickness and based on the change of the speed ratios as well as the effective direction angle, the effective tool angles are dynamic values corresponding to time and vibration period. Equations for the effective rake angle $\gamma_{o,eff}$ and clearance angle $\alpha_{o,eff}$ contain the tool specifications for rake angle γ_o , clearance angle α_o , point angle σ as well as the cutting velocity v_c and feed velocity $v_z(t)$. For drilling tools, rake angle and clearance angle depend on the considered position of the cutting edge, respectively, the considered radius r . While focusing on the cutting-edge corner, Eqs. (21) and (22) describe the effective angles, including the dynamic characteristic. Compared to low-frequency vibration-assisted drilling, UAD leads to significant periodical changes of the effective angles and therefore of the cutting conditions.

Fig. 5 Phase shift and feed modulation in UAD

Fig. 6 Speed characteristic in ultrasonic-assisted drilling

$$\begin{aligned}\gamma_{o,eff}(t) &= \gamma_o + \tan^{-1} \left(\frac{v_z(t) \cdot \sin\left(\frac{\sigma}{2}\right)}{v_c} \right) \\ &= \gamma_o + \tan^{-1} \left(\frac{(v_f + A \cdot \omega_{US} \cdot \cos(\omega_{US} \cdot t + \varphi_0)) \cdot \sin\left(\frac{\sigma}{2}\right)}{(\pi \cdot D \cdot n)} \right)\end{aligned}\quad (21)$$

$$\begin{aligned}\alpha_{o,eff}(t) &= \alpha_o - \tan^{-1} \left(\frac{v_z(t) \cdot \sin\left(\frac{\sigma}{2}\right)}{v_c} \right) \\ &= \alpha_o - \tan^{-1} \left(\frac{(v_f + A \cdot \omega_{US} \cdot \cos(\omega_{US} \cdot t + \varphi_0)) \cdot \sin\left(\frac{\sigma}{2}\right)}{(\pi \cdot D \cdot n)} \right)\end{aligned}\quad (22)$$

Regarding the effective clearance angle, negative values are possible, especially for high vibration amplitudes and frequencies as well as low clearance angles and cutting speeds. This leads to a plowing effect in UAD, shown in Fig. 7. The tool, simplified as cutting edge without cutting-edge radius in orthogonal plane, follows the

ultrasonic-assisted tool path according to Eq. (7). While the process velocity in feed direction v_z reaches high values, caused by the forward motion of the ultrasonic vibration, the effective clearance angle takes on negative values. Therefore, the flank face of the cutting edge hits the already manufactured wavy surface of the workpiece. For each vibration, a certain contact area A_p as a value representing the magnitude of plowing can be expressed. In drilling, cutting speed decreases towards the centre of the tool. Therefore, all process configurations in UAD lead to plowing below a critical radius $r_{p, crit}$. With respect to the cutting edge corner, a critical rotation speed $n_{p, crit}$ occurs.

$$n_{p,crit} = \frac{(v_f + A \cdot \omega_{US}) \cdot \sin\left(\frac{\sigma}{2}\right)}{\pi \cdot D \cdot \tan(\alpha_0)} \quad (23)$$

The plowing effect influences the thrust force [37]. Therefore, especially at the point of the cutting-edge corner,

Fig. 7 Plowing in UAD

plowing affects burr formation. Taking into account the critical speed contributes to a process design, especially the setup of a suitable rotation speed.

3 Aspects of process design

Regarding the kinematic model, one fundamental principle of UAD is the modulation of feed and uncut chip thickness. For this purpose, a process setup with a maximum modulation effect leads to an effective usage of the ultrasonic vibration. Aiming a maximum of modulation, a defined phase shift of 180° is optimal. Regarding application of UAD, this leads to the demand of synchronization of ultrasonic vibration frequency and rotation speed. This approach is well known for vibration-assisted machining, especially vibration-assisted turning with low frequencies [41, 42, 44, 50]. In addition, the ratio between feed per tooth and ultrasonic amplitude, respectively, the minimum of the dynamic feed, defines the fundamental process characteristics in terms of intermitted and continuous cutting. In case of a phase shift of 180° , a direct calculation of the minimum feed $f_{z, \min}$ is possible.

$$f_{z, \min} = \frac{f}{Z} - 2 \cdot A = f_z - 2 \cdot A \quad (24)$$

Figure 8 shows three characteristic process scenarios determined as “Interrupted” for the intermitted cutting, “Continuous” for continuous cutting and “Squeeze” for the special case in between. In this context, the characteristic value K_z is suitable to differentiate the scenarios easily.

$$K_z = \frac{f}{2 \cdot Z \cdot A} \quad (25)$$

A value $K_z < 1$ indicates intermitted cutting with a periodical interrupted cut, where the tool loses contact to the workpiece. This process scenario causes discrete chips related to the ultrasonic frequency and a periodical abrupt tool load. For values of approx. 1, the minimum feed is 0. Therefore, uncut chip thickness is below the minimum chip thickness for a significant period, leading to material squeezing. Practical applications of UAD should avoid this scenario. Regarding values of $K_z > 1$, continuous cutting occurs with modulated feed and uncut chip thickness. Based on the kinematic model, chips show periodic areas with high and low chip thickness. Thus, chips provide breaking points, resulting in improved chip breaking behaviour but larger chips occur compared to the scenario of intermitted cutting. Correlating to the dynamic feed and uncut chip thickness, the tool load exhibits a dynamic but continuous characteristic, avoiding abrupt tool unload and load.

Aiming to set up the modulation effect in UAD, a defined phase shift is necessary. In this context, a synchronization of ultrasonic frequency and rotation speed is suitable to achieve a defined phase shift. Regarding application of this synchronization for UAD, it is essential to use a closed loop control of the spindle rotation speed. Usually ultrasonic systems apply a closed loop control for the ultrasonic frequency, maintaining the resonance excitation during drilling process. Therefore, the value of frequency during operation is not known a priori. A practical solution is drilling a test hole estimating the operation frequency. Thereby, it is possible to set up the rotation speed, aiming at a phase shift of 180° . The definition of the favourable scenario depends on specific process demands. Feed and ultrasonic amplitude are both suitable parameters. Due to limited vibration amplitudes, it is a common method to adjust feed according to the maximum amplitude and aimed

Fig. 8 Process scenarios in UAD

scenario. Because of the adjustment of amplitude and feed, a reliable and constant vibration amplitude is necessary during the entire operation time, especially during the drilling process. To satisfy this demand, the ultrasonic system needs a closed loop control for the amplitude as well.

4 Experimental setup

The experimental investigations aim to verify the kinematic process model and the aspects of process design. Table 1 shows the experimental setup of test series 1 to investigate the synchronization of vibration frequency and spindle speed. Table 2 shows the experimental setup of test series 2 related to the correlation between vibration amplitude and feed. The test series include three repetitions for each parameter setup. Drilling tests were carried out according to the defined process scenarios. The following chapter covers the experimental setup including the system for UAD, the choice of the tool and process parameters. Moreover, a method for acoustic in-process measurement contributes to evaluate process properties of UAD.

In general, vibration systems for the excitation of either the workpiece or the tool are able to realize UAD. Due to the demand of flexibility as well as high and reliable vibration amplitudes devices for the excitation of the workpiece are not able to satisfy industrial demands. Therefore, systems for UAD usually consist of an active tool holder with integrated piezoelectric actuators generating the ultrasonic vibration. To reach high amplitudes, the system is excited in a resonant mode shape of the mechanical structure, including the drilling tool. Hence, the geometry of the tool, especially the tool shaft, affects shape and parameters of the ultrasonic vibration. Usually, ultrasonic tool holders are designed to excite the longitudinal mode shape. However, using twisted drilling tools torsional vibrations, superimposing the longitudinal vibration, occur. The proposed kinematic process model covers only the longitudinal shape with orientation in feed direction. Therefore, a straight non-twisted drilling tool is used for the experiments to assure one-dimensional vibration in feed

direction. The step-drill has a clamping diameter of 8 mm and a primary drilling diameter of 5.7 mm. The drilling tests use only the first part and therefore the primary drilling diameter. The drill is a special aluminium-drilling tool JEL® from KOMET Group (type PKD-BRL 5,7/6H7 IK) made of solid carbide with included diamond blanks. The clearance angle on the cutting edge corner is 7° and the rake angle is 0°.

Drilling tests have been carried out using a 4-axis machining centre HEC 500D XXL from Starrag Heckert and a self-developed ultrasonic system according to [51] shown in Fig. 9. Special properties of the system are the closed loop control of the ultrasonic frequency to maintain resonance as well as closed loop control of the vibration amplitude and the capability of vibration amplitudes up to 20 μm . An ultrasonic generator, including the control system, provides the active tool holder with energy via an inductive energy transmission device. Integrated piezoelectric actuators excite the sonotrode, including the tool mounted via a shrinking chuck. A piezoelectric sensor integrated into the transducer of the resonant vibration system [52, 53] generates a characteristic signal according to the mechanical vibration. A radio device transmits this signal from the rotary tool holder to the stator mounted on the machine spindle. A cable transmits the signal to the generator, where the signal is the basic variable for the closed loop control system. This system is capable to assure resonance as well as a constant vibration amplitude during the drilling process, which is fundamental to verify the kinematic process model. Table 3 shows key properties of the ultrasonic system. Figure 10 presents measurements of the vibration amplitude performed with a laser vibrometer (Polytec GmbH, type CLV-2534). The abscissa of the diagram is the setting of the generator's amplitude level. The ordinate shows the vibration amplitude of the tool tip as peak to peak value and the generator power under free condition without drilling process.

As described in Chapter 3, the process design, especially the choice of the rotation speed to adjust a defined phase shift, is based on the kinematic model and on the estimation of the operation frequency during the drilling process. Tables 1 and 2 summarize related parameters. The frequency $f_{US}(calc)$ describes the estimated operation frequency used for the calculation of spindle speed n aiming for a defined phase shift $\varphi_D(calc)$. The workpiece is a test block with the size 200 mm $\times$ 130 mm $\times$ 40 mm made of EN AW-7075 T6 (AlZn5,5MgCu). Table 4 presents the physical and mechanical properties of the material. During the drilling process, there are several disturbance variables affecting the phase shift. Due to the closed loop control of the spindle speed, deviations of rotation speed are neglected. In contrast, the ultrasonic frequency includes several deviations towards the estimated operation frequency that lead to errors regarding the a priori-defined phase shift. Figure 11 shows the frequency course of

Table 1 Experimental parameters test series 1

	UAD P1	UAD P2	UAD P3
f [mm]	0.05	0.05	0.05
v_c [m/min]	147.6	147.2	146.8
n [min ⁻¹]	8243.94	8222.07	8200.32
v_f [mm/min]	412.2	411.1	410
A [μm]	6	6	6
$f_{US}(calc)$ [Hz]	25831	25831	25831
$\varphi_{US,D}(calc)$ [°]	0	90	180

Table 2 Experimental parameters test series 2

	UAD 1	UAD 2	UAD 3	CD 1	CD 2
Scenario	“Interrupted”	“Continuous”	“Squeeze”	-	-
f [mm]	0.02	0.05	0.025	0.02	0.05
v_c [m/min]	148	148	148	148	148
n [min ⁻¹]	8253.369	8253.369	8253.369	8253.369	8253.369
v_f [mm/min]	165	413	206	165	413
A [μm]	6	6	6	-	-
$f_{US(calc)}$ [Hz]	25723	25723	25723	-	-
$\varphi_{US,D(calc)}$ [°]	180	180	180	-	-

UAD 1 with the periods of scanning, free vibration and operation as well as the different deviations, exemplarily. The generator starts with a constant frequency for one second. Afterwards the scanning procedure starts with a sweep with decreasing frequency aiming to identify and to catch the resonance frequency. During the status of free vibration, the tool is unloaded and the closed loop control for frequency and amplitude is active. The load of the drilling process causes an increase of resonance frequency and damping. Via the closed loop control, the operating frequency increases according to the resonance frequency and in parallel the electric power increases to maintain the vibration amplitude. The two pictures below the general course show the characteristic of the operating frequency during drilling in detail. Deviations during this period, classified as static and dynamic deviations, affect the phase shift of the process kinematics. The static deviation $\Delta f_{US, stat}$ is defined as the difference between estimated operation frequency and the mean value of the real operation frequency $f_{US(mean)}$. In addition, a dynamic deviation $\Delta f_{US, dyn}$ occurs, characterized by the frequency fluctuation during the process. The frequency change during the drilling process is due to the highly dynamic frequency control, which reacts to diverse changes of process conditions and the characteristics of the inductive energy transmission. Both

frequency deviations affect the value of phase shift via a static and a dynamic deviation $\Delta \varphi_{US, D, stat}$ and $\Delta \varphi_{US, D, dyn}$ according to Eq. (16). Therefore, it is important to keep them low enough to realise constant process properties including the defined phase shift. Regarding the experimental tests, the operation frequency of the generator was measured to calculate the deviations and assure defined phase shift.

In addition to frequency and phase shift, chips and the wall of the hole were analysed to evaluate process properties. Regarding a measuring setup for UAD, the literature shows a wide use of force measurements contribute to the comparison of different parameters of UAD and conventional drilling with mean or low-pass filtered signals. Force measurements were not used to identify the dynamic behaviour of the force values due to the vibrating tool motion so far. For common force measurement devices, ultrasonic frequency is higher than the first own frequency of the measuring device and reach the domain of structural quasi-continuum with solid wave propagation. Therefore, the experimental investigations use a new method with acoustic measurements to evaluate UAD. In this context, the induction of the ultrasonic vibration into the process zone leads to additional acoustic effects. Regarding the interaction of high power ultrasonic waves with low-frequency waves, modulation effects occur [54]. In this

Fig. 9 Experimental setup

Table 3 Key properties of the ultrasonic system

Property	Unit	Value
Generator—manufacturer	-	DEVAD GmbH (Germany)
Generator—type	-	UIP1000hdT with custome modification
Generator—max. power	[W]	1000
Generator—closed loop control	-	Frequency and amplitude
Energy transmission—type	-	Inductive
Energy transmission—max. power	[W]	≈ 300
Signal transmission—type	-	Radio
Signal transmission—frequency	[GHz]	5.8
Tool holder—interface	-	HSK A63
Tool holder—shrinking diameter	[mm]	8
Piezoelectric actuators—manufacturer	-	CeramTec GmbH (Germany)
Piezoelectric actuators—material	-	Sonox® P8
Piezoelectric actuators—size	[mm]	2x (Ø50x5)
Piezoelectric sensor—manufacturer	-	CeramTec GmbH (Germany)
Piezoelectric sensor—material	-	Sonox® P8
Piezoelectric sensor—size	[mm]	1x (Ø50x5)

case, modulation is defined as the interaction of these two signals in frequency domain, also known as intermodulation. This leads to sidebands in the frequency domain located besides the ultrasonic frequency and its harmonic and subharmonic representatives with an offset according to the value of the corresponding low frequency. Therefore, it is possible to use the ultrasonic wave as a carrier signal for information, especially regarding process instabilities and process vibrations, e.g. chatter, directly from the process zone. Wurpts (2016) [55] verified this modulation effect for ultrasonic vibration systems in case of a simple impact contact to a surface. The benefit of this approach is the well-defined identification of process-relevant vibrations. Acoustic measurements used an acceleration sensor (PCB Piezotronics, type M352A60) to measure process-related vibrations. The experimental tests aim for the investigation of the modulation

effects of UAD as well as the process model including the defined process scenarios.

5 Experimental results and discussion

According to Eq. (16), Tables 5 and 6 show the static and dynamic deviations $\Delta\varphi_{US, D, stat}$ and $\Delta\varphi_{US, D, dyn}$ of the phase shift during the drilling operation of the two test series. The values are calculated based on the ultrasonic frequency acquired from the generator voltage during the drilling tests. The static deviation is low enough and thus does not initiate a change of the characteristic process scenarios during the drilling tests via deviations of the phase shift. The dynamic deviation shows a fluctuation around the mean ultrasonic frequency, while the mean frequency stays constant over the

Fig. 10 Measurement of vibration amplitude

Table 4 Physical-mechanical properties of aluminium alloy EN AW-7075 T6

Property	Unit	Value
Density	[g/mm ³]	2.8
Melting Point	[°C]	480–640
Electrical conductivity	[m/(Ω*mm ²)]	19–23
Thermal conductivity	[W/(m*K)]	130–160
Heat capacity	[J/(kg*K)]	862
Tensile strength	[MPa]	530
Yield strength	[MPa]	460
Modulus of elasticity	[GPa]	71
Elongation	%	5

Table 5 Operation deviations for frequency and phase shift for test series 1

	UAD P1	UAD P2	UAD P3
$f_{US}(calc)$ [Hz]	25831	25831	25831
$\varphi_{US, D}(calc)$ [°]	0	90	180
$\Delta f_{US, stat}$ [Hz]	0.9	1.6	2.6
$\Delta f_{US, dyn}$ [Hz]	± 18	± 18	± 21
$\Delta \varphi_{US, D, stat}$ [°]	1.2	2,1	3,4
$\Delta \varphi_{US, D, dyn}$ [°]	± 23.6	± 23.6	± 27.7

operation time. Especially for test sequences “UAD 1” and “UAD 3” in test series 2, single ultrasonic periods can induce states different from desired “Interrupted” or “Squeeze” effect.

Fig. 11 UAD P1—graph of operating frequency including static and dynamic deviations

Table 6 Operation deviations for frequency and phase shift for test series 2

	UAD 1	UAD 2	UAD 3
Scenario	“Interrupted”	“Continuous”	“Squeeze”
$f_{US, calc}$ [Hz]	25723	25723	25723
$\varphi_{US, D, calc}$ [°]	180	180	180
$\Delta f_{US, stat}$ [Hz]	1	27	0
$\Delta f_{US, dyn}$ [Hz]	± 25	± 15	± 25
$\Delta \varphi_{US, D, stat}$ [°]	1.3	31.3	0
$\Delta \varphi_{US, D, dyn}$ [°]	± 32.7	± 19.6	± 32.7

Further analyses about the dynamic behaviour of the ultrasonic frequency are necessary to quantify the impact of the dynamic deviations.

Figure 12 shows chips of the test series 1. The influence of the phase shift and the related modulation of uncut chip thickness is visible through the different size of the chips. “UAD P1” with a phase shift of 0° and “UAD P2” with a phase shift of 90° provide a mixture of long and shorter chips. “UAD P3” with a phase shift of 180° and maximum modulation shows only short chips that are comparable to the short chips of “UAD P1” and “UAD P2”. “UAD P1” with 0° phase shift does not provide a modulation of uncut chip thickness. Therefore, the chips are significantly longer compared to “UAD P3” with a maximum phase shift of 180° , but in the same time, there are also short chips. This is related to the increase of chip curvature during UAD that also cause shorter chips and is independent from the modulation effect. Thus, UAD improves chip breaking also without modulation and synchronization. During the test series, the dynamic phase deviation could affect the results because in terms of aiming a phase shift of 0° , the deviation cause an increase of the modulation effect. Additional tests with a lower dynamic

deviation via adapted control parameters or an optimized inductive energy transmission are suitable to clarify this.

Figure 13 illustrates chips of selected drilling tests from test series 2. Compared to conventional drilling in “CD 1”, the ultrasonic-assisted drilling without intermitted cutting in “UAD 2” shows improved chip breaking due to the feed modulation and decrease radius of chip curvature. Drilling test “UAD 1”, according to the process scenario “Interrupted”, generates chips with the shape of a needle. Due to the intermitted cutting, each ultrasonic vibration period produces a single chip. In the same way, this effect verifies the theory of phase shift and process scenarios with adapted amplitude and feed for ultrasonic-assisted drilling. Regarding the application of UAD, chips of “UAD 2” with continuous cutting conditions are favourable. While the long chips of conventional drilling could lead to chip jam or chips stuck on the tool, needle chips due to “UAD 2” are difficult to remove from the working space of the machine tool.

The acoustic in-process measurement provides the acceleration time data of the acceleration sensor mounted on the workpiece according the experimental setup. Analysing UAD with short-time fast Fourier transform (STFFT) converts time data into the frequency domain. Figure 14 and Fig. 15 illustrate the sonogram and STFFT for “UAD 1” and Fig. 16 gives an overview of “CD 1”, “UAD 1” and “UAD 2”. Table 7 shows characteristic frequencies and magnitudes for the drilling tests. Compared to UAD, the magnitudes for CD are under range. According to Fig. 14, a characteristic sequence is visible for UAD. The ultrasonic vibration starts prior to the drilling process. Measured acceleration magnitudes are transmitted via air. During the drilling process, the ultrasonic frequency is dominant. In addition, harmonics and subharmonics of the ultrasonic frequency occur. Furthermore, sonogram and STFFT show modulation effects. Low frequencies generate sidebands next to the ultrasonic

Fig. 12 Shape of chips from test series 1

Fig. 13 Shape of chips from test series 2

frequency. The occurrence and magnitude of the sidebands correlate with the process stability. Therefore, intermittent cutting in “UAD 1” causes process instabilities. Through simulative and experimental modal analysis, the two lower frequencies, named as process frequencies f_{P1} and f_{P2} , are identified as eigenfrequencies with bending modes of tool and sonotrode. Due to the interaction of the low frequencies with the dominant ultrasonic frequencies, each process frequency causes a lower and an upper sideband with $f_{P, ls}$ and $f_{P, us}$. Magnitudes of process frequency and sidebands correlate. In detail, the ratio depends on the complex interaction mechanisms of phase and amplitude modulation of the different

resonant vibrations, including the transmission to the point of measurement. The experimental results show an increase of the magnitude of the sidebands according to the process frequencies. Hence, the evaluation of the modulation effect shows the potential to be a suitable method to evaluate process stability in UAD. Furthermore, the defined process scenarios generate a specific signal characteristic, each. Therefore, the acoustic in-process measurement is a suitable approach to identify the process scenarios according to the kinematic model. The interrupted cutting conditions cause a periodic abrupt tool load, which could lead to the process instabilities in terms of unfavourable tool bending vibrations. The continuous

Fig. 14 Acceleration sensor—sonogramm of “UAD 2”

Fig. 15 Acceleration sensor—short-time fast Fourier transform (at 20 s) of “UAD 2”

Fig. 16 Acceleration sensor—overview for sonogram and short-time fast Fourier transform

Table 7 Significant frequencies and magnitudes

	CD 1	UAD 2	UAD 1
Scenario	-	“Continuous”	“Interrupted”
f_{US} [Hz]/ a_{US} [m/s ²]	-	25750/551.8	25725/536.2
f_{P1} [Hz]/ a_{P1} [m/s ²]	-	-	1600/9.4
$f_{P1, ls}$ [Hz]/ $a_{P1, ls}$ [m/s ²]	-	-	24125/28.0
$f_{P1, us}$ [Hz]/ $a_{P1, us}$ [m/s ²]	-	-	27325/325.3
f_{P2} [Hz]/ a_{P2} [m/s ²]	-	3575/0.7	3450/27.0
$f_{P2, ls}$ [Hz]/ $a_{P2, ls}$ [m/s ²]	-	22175/10.8	22225/162.3
$f_{P2, us}$ [Hz]/ $a_{P2, us}$ [m/s ²]	-	29325/29.4	29175/49.2

cutting conditions cause a periodic but continuous change of the tool load. For this case, the results show no additional tool vibration and a higher process stability.

In addition, Fig. 17 shows microscopy pictures of the ground and wall of the hole. The pictures of the ground of the UAD tests show a characteristic wavy surface structure related to the ultrasonic frequency, respectively, the number of ultrasonic vibration periods per tool rotation. Furthermore, pictures of “UAD 1” with intermitted cutting and process instabilities exhibit an additional star-shaped structure on the bore ground. The estimated frequencies generating this structure are similar to the first process frequencies of “UAD 1” and match with characteristic of a bending mode of a tool during the drilling process. Moreover, the ultrasonic motion

and the impact of the bending mode are visible also on the structure of the wall.

6 Conclusion

A kinematic analysis of the path of the cutting edge, respectively, the cutting-edge corner, enables a new approach for the process design of ultrasonic-assisted drilling. Limited to drilling with defined cutting edge and longitudinal tool oscillation, the parameters dynamic feed per tooth $f_{z, dyn}$ and phase shift $\varphi_{US, D}$ characterize the drilling process with ultrasonic assistance. The phase shift describes the offset of the ultrasonic waves of the machined surface structure towards the current sinusoidal tool path. The kinematic model shows the modulation of feed and uncut chip thickness to be a fundamental effect for UAD. For this purpose, a phase shift of 180° generates the highest modulation effect. To adjust phase shift, it is necessary to synchronize rotation speed and ultrasonic operation frequency. Through dynamic feed per tooth, and especially its minimum value, characteristic process scenarios show the fundamental effects of different process configurations while “Continuous” is continuous drilling with modulated feed and “Interrupted” is drilling with intermitted cutting. Furthermore, secondary effects occur. UAD can lead to negative clearance angles and plowing effects. Depending on the shaft geometry of the tools, superimposed vibrations, e.g.

Fig. 17 Microscopy of bore ground and wall

torsional vibrations, appear. Therefore, the kinematic model is valid for one dimensional longitudinal vibrations in feed direction, in detail for straight non-twisted drilling tools.

A self-developed system for UAD was used to perform drilling tests related to the presented process scenarios. Especially the shape of the produced chips exhibits characteristic properties. Investigations of the influence of the phase show that the modulation effect causes shorter chips. In contrast, UAD with disabled modulation produce shorter chips too, which is supposed to be related to the increase of chip curvature in UAD. The experiments considering the relation between feed and vibration amplitude aim to investigate the properties of the different process scenarios. While UAD with continuous and modulated feed causes improved chip breaking, UAD with intermitted cutting generates needle shaped chips related to the ultrasonic frequency and rotation speed. Furthermore, a new approach using acoustic modulation effects was introduced assessing the process stability in UAD. Based on this method, drilling tests with intermitted cutting show significant process instability, resulting in bending vibrations of the tool and characteristic markers on the bore ground.

In summary, drilling tests verify the kinematic process model as well as the aspects of process design. Thereby, the knowledge of the fundamental principles leads to a better understanding of the mechanisms and more effective application of UAD. Regarding the experimental results, the process scenario of continuous UAD is favourable because the interrupted cutting causes process instabilities. Moreover, the needle chips are difficult to remove from the working space of the machine tool. Further research focuses on the implementation of superimposed vibrations, e.g. torsional vibrations, the entire cutting-edge course and the cutting-edge radius as well as the extension of the acoustic in-process measurement to a suitable monitoring system.

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