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Development of a System for Ultrasonic Die Oscillations during Extrusion of Aluminum Hollow Profiles

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Abstract. High friction in aluminum hollow profile extrusion limits material flow, process stability, and productivity. Ultrasonic vibration offers a promising approach to reduce friction, yet its application to industrial porthole dies is still insufficiently explored. This study presents the development and investigation of an ultrasonic die sonication system for aluminum extrusion. Finite element extrusion simulations demonstrate that reduced friction leads to lower extrusion forces, decreased profile exit temperatures, and improved material flow. A modified porthole die enabling ultrasonic excitation at multiple positions was designed accordingly. The vibrational behavior of the die was analyzed using three-dimensional modal and harmonic finite element simulations. Suitable excitation frequencies between 18.5 and 23 kHz were identified and experimentally validated by laser vibrometry, confirming effective transmission of ultrasonic vibrations into the die. The simulation results demonstrate the feasibility of ultrasonic die oscillation for aluminum hollow profile extrusion and provide a solid basis for forthcoming extrusion trials and further process optimization. The system was implemented, approved, and is now available for upcoming experimental trials.

Introduction

Conventional extrusion of metallic materials is often limited by high forming forces and material flow, strongly influenced by friction conditions between billet material and container, ram and die [1]. Hence, friction can limit the manufacturability of complex profile cross sections such as very thin profile segments or very wide profiles. To address these limitations, friction can be reduced e.g. by applying lubricants. However, in light metal extrusion lubrication often is avoided, especially in case of porthole die extrusion. If the lubricant reaches into the welding chamber of a porthole die, seam weld quality could be reduced significantly. The increasing demand for high-performance metal profiles with superior dimensional accuracy, high productivity and surface quality has placed significant pressure on traditional extrusion processes. Another approach to reduce friction in forming processes are advanced assisted forming technologies e.g. involving vibration or ultrasonic excitation.

Research in various metal forming contexts and on a wide range of materials, including extrusion [2], drawing [3], and upsetting [4] has consistently shown that ultrasonic vibration can lead to a significant reduction in required forming forces and friction effects at the die–workpiece interface, although the magnitude of these effects depends strongly on vibration parameters and material properties [5]. Experimental studies have documented, that under ultrasonic excitation, the mean forming force can decrease notably, while oscillatory components of the force signal reflect complex dynamic interactions at the tool interface [6]. Related work in micro-forming and micro-extrusion contexts has similarly demonstrated that ultrasonic vibration can improve surface quality and reduce forming load, reinforcing the potential of ultrasonic assistance for high-precision forming task [7].

Despite these results, efficient transmission of ultrasonic energy in large-scale industrial extrusion tools continues to pose engineering challenges, as sustaining stable high-power ultrasonic excitation under heavy mechanical loads can lead to reduced amplitude and effectiveness. Hence, this study presents a first step to investigate the effect of die sonication on the extrusion process and profile properties.

Materials and Experimental Setup

Extrusion Simulation. In order to investigate the potential effects of e.g. reduced friction conditions between porthole die (H11 steel) and aluminum billet material (EN AW-6060) through die sonication, FEM simulations were conducted applying different friction coefficients. Conventional extrusion without die sonication was simulated in DEFORM$^{®}$3D using a Tresca friction model with a friction factor of $m=0.7$ between the die and the aluminum billet. In addition, a previously developed friction model accounting for temperature and normal pressure at the contact interface was applied for comparison [8,9,10]. To investigate the potential influence of die vibration, no direct simulation of high-frequency oscillations was performed. Instead, the vibration-induced reduction in friction was represented by prescribing lower Coulomb friction coefficients. Based on literature data for extrusion processes under high-frequency die oscillation [11], Coulomb friction coefficients of $\mu=0.1$ and $\mu=0.05$ were assumed. This approach allows the isolated assessment of the mechanical consequences of a reduced friction level without explicitly modeling the oscillatory motion of the die. Since the use of coulomb friction is not common for aluminum extrusion simulations, a reduced Tresca friction coefficient of $m=0.1$ was selected as well. The simulation model is given in Fig. 1a. It consists of a prefilled die and a billet length of 160 mm. A ram velocity of $v_{ram}=5$ mm/s was applied. Billet and container temperatures were set to $T_B=T_C=500$ °C, die temperature to $T_{die}=470$ °C and ram temperature to $T_{ram}=460$ °C. Zener Holomon model was applied to calculate flow stresses of EN AW-6060 billet material. Necessary material constants were determined via hot compression tests to $A=3.0\cdot10^{-19}\,s^{-1}$, $\Delta H=155.0$ kJ/mol, $n=6.8$ and $\alpha=0.0016\,MPa^{-1}$. Transient simulations were performed using Lagrange algorithm. Extruding the profile cross section given in Fig. 1b from a container with $D_C=125$ mm leads to an extrusion ratio of R=28:1.

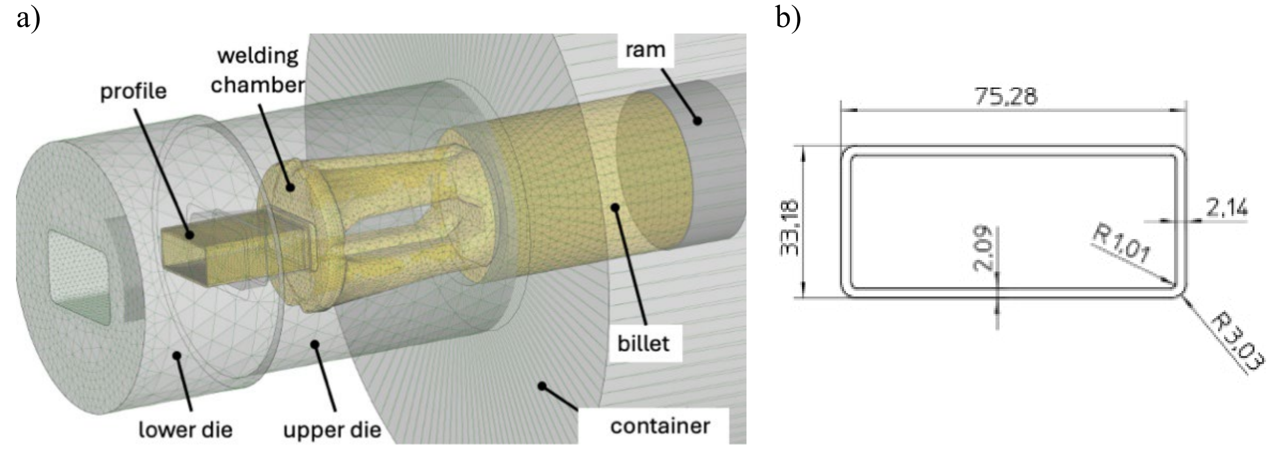

Fig. 1. a) FEM-model for extrusion simulation in DEFORM$^{®}$3D b) profile cross section

Setup sonication system. The specialized german company *MTH Ultraschalltechnologie GmbH & Co. KG* was consulted for suitable components to build an applicable die sonication system. Similar to recent literature [2, 7], this system consists of a high-frequency generator (HF) type K5 (2000 W / 20 kHz), a sonotrode (sonication head) type USK 3020 (3000 W, 20 kHz), a titanium ultrasonic booster (20 kHz, transmission ratio 1:1) as well as a high-frequency transmission cable.

The basic principle of this system is that the HF-generator produces a frequency of about 20 kHz that is transmitted to the converter. The converter transfers the high-frequency electric alternating current into mechanical oscillations. The flat-faced surface of the sonotrode vibrates according to the frequency determined by the HF-generator and with amplitudes between 6 µm to 12 µm. The sonotrode is attached to the porthole die via a coupling screw. Hence, HF-oscillations can be transmitted from the sonotrode onto the porthole die.

For investigations regarding application of high-frequency oscillations onto an extrusion die, a pre-existing porthole die out of the inventory of the extrusion R&D center at TU Berlin (FZS) was selected. The die featured four portholes and was applicable for a container diameter of 125 mm. Since later extrusion tryouts should be carried out on the 8.2 MN extrusion press at the FZS TU Berlin, potential positions for placing the sonotrode had to be identified. Thus, the CAD model of this extrusion press was applied. Fig. 2 shows suitable positions that allow integration of the die sonication system. The implemented tool design allows ultrasonic excitation at angular positions of 0°, 30°, 60°, 120°, 240°, 270°, and 300° distributed around the tool circumference. Due to the symmetric properties of the die, position 60°, 120°, 240° and 300° are positionally symmetric. Regarding future comparison the position depths of the named positions are varied (2, 8 and 14 mm) and an axial shift is applied at 240°.

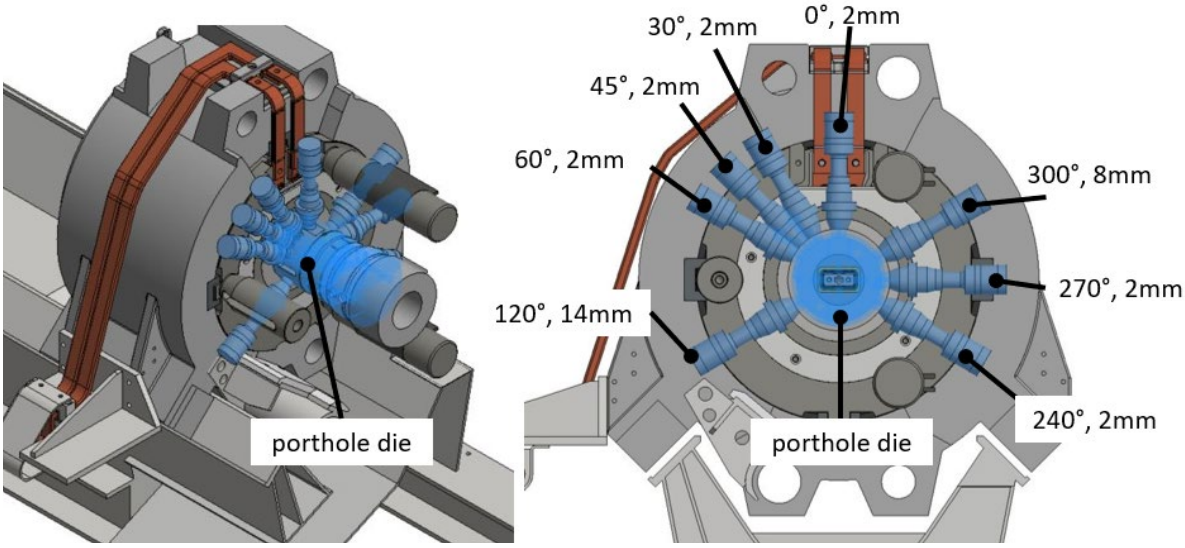

Fig. 2. Possible locations for placing sonication system on the die within the 8.2 MN extrusion press at FZS TU Berlin

The modification of the porthole die contains manufacturing planar segments onto the round die surface. The planar segments enable the transmission of sonotrode oscillations onto the porthole die. Each planar segment featured a threaded hole for a coupling screw that connects sonotrode and die. A new mandrel head has been manufactured and is attached to die with two screws. In addition, multiple drill holes were integrated, to enable direct measurement of the profile exit temperature within the die bearing channel using contact thermocouples. Thereby, experimental data for validation of the process simulations can be determined. The adapted die is displayed in Fig. 3. Modifications were conducted by the die manufacturer *WEFA Singen GmbH (Germany).*

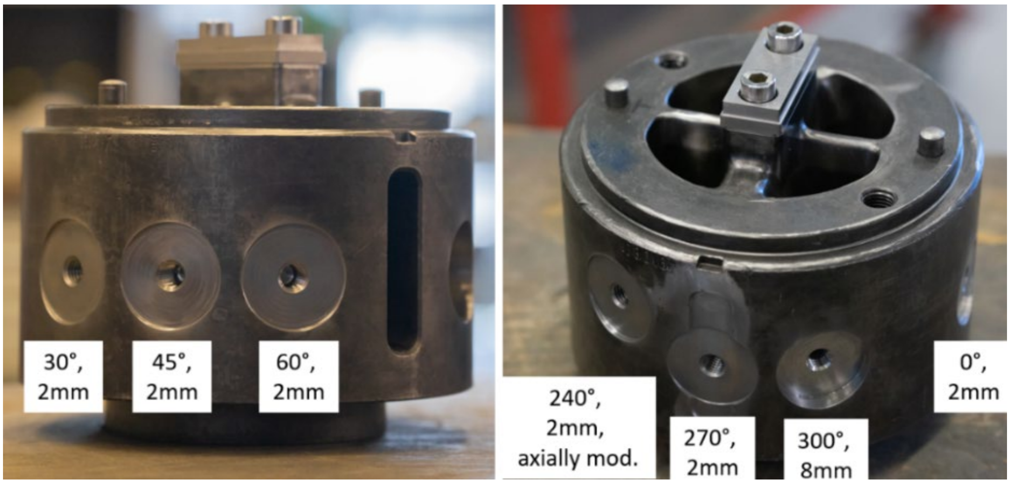

Fig. 3. Upper die after modification featuring new mandrel head as well as multiple vibration excitation positions

Numerical modelling of ultrasonic die excitation. The vibrational behavior of the extrusion die under high-frequency excitation is analyzed by a three-dimensional finite element model of the die implemented in the software tool COMSOL Multiphysics 6.0. The excitation positions are realized in the die geometry as cylindrical recesses as manufactured in the experimental setup. The internal porthole and bearing channels are modelled as continuous hollow cavities extending from one axial end face of the die to the other, thereby allowing direct assessment of the vibrational response within the flow paths.

The die was assigned a homogeneous, isotropic and linear-elastic material corresponding to a hot-work tool steel of type H11 taken from the COMSOL material library.

The mesh quality is verified with a convergence plot, displaying the eigenfrequencies as a function of the mode number for varying maximum element sizes. For this purpose, a parametric sweep was conducted using standardized meshing options in COMSOL, varying the maximum element size between 3.5 cm and 1.5 cm.

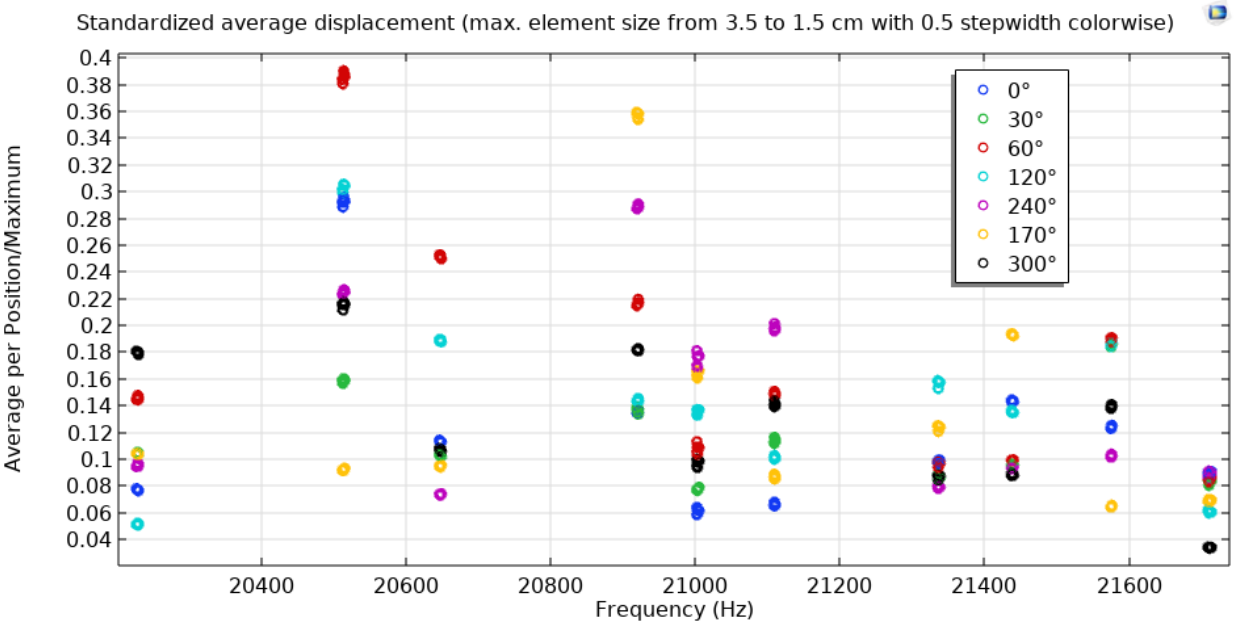

Fig. 4. Standardized average deflection per excitation position varying in maximum element size per color

The results in Fig. 4 confirmed that the computed eigenfrequencies remained consistent across the different mesh refinements. Variations of circles within the same color represent horizontal frequency deviations and vertical average displacement. No systematic correlation is observed between the maximum element size and the direction of change (positive or negative). Although the maximum deviation reaches approximately 5%, the mean deviation remains below 1%, thereby confirming the mesh independence of the modal analysis.

First, an eigenfrequency analysis of the die was carried out to identify natural frequencies and modes around 20 kHz. Of particular interest were modes exhibiting simultaneously high vibration amplitudes at one of the predefined excitation positions and within the internal flow channels. In preparation for an off-line excitation test on the die outside the press, a modal analysis without boundary constraints was analyzed. This configuration was used to investigate whether the ultrasonic excitation can already produce measurable vibration patterns in the unsupported die and to provide a reference case for the mounted condition. In a second configuration, the mechanical boundary conditions were chosen to reflect the kinematic constraints of the die when mounted in the extrusion press (Fig. 5). In the mounted configuration, both axial end faces of the die were constrained in axial direction by roller conditions, allowing radial and circumferential deformation while suppressing rigid-body motion along the press axis. This represents the guidance of the die within the press stack without over-constraining it in the radial direction (Fig. 11).

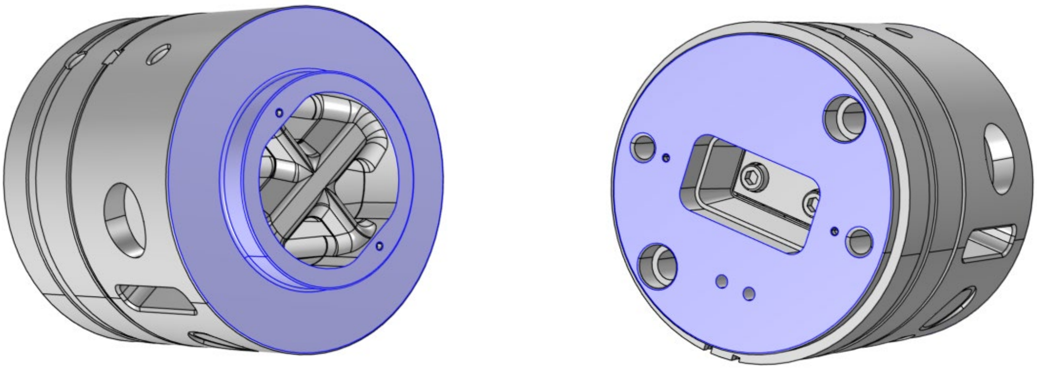

Fig. 5. Porthole die with highlighted boundary areas

Second, a harmonic oscillation was introduced on the die performed in the frequency-domain. The excitation by the ultrasonic system was introduced into the model via a boundary load acting on the sonotrode area.

Instead of prescribing a displacement boundary condition, a harmonic volumetric force density was applied (Eq. 1), where ρ is the material density of the sonotrode, f is the excitation frequency, A is the prescribed displacement amplitude and f_n is the local surface normal direction of the contact interface.

$$f_n = \rho \times (2\pi f)^2 \times A \tag{1}$$

This formulation avoids numerical issues associated with mixed displacement and force boundary conditions. As the study aims at the relative distribution of amplitudes in the die rather than their absolute magnitude, the specific value of A is not critical but is chosen regarding the specifications of the experimental setup. Covering frequencies between 18.5 kHz and 23 kHz in increments of 0.5 kHz matches the operating range of the available ultrasonic equipment. Additional exploratory simulations with an extended frequency range were conducted to assess the potential of alternative excitation concepts but are not discussed in detail here. For each excitation position the corresponding sonotrode area was activated individually, so that the influence of the excitation location on the vibrational response of the die and on the oscillation amplitudes within the flow channels could be systematically evaluated.

Results

Table 1 shows a comparison of the extrusion forces and maximal profile exit temperatures determined by FEM for the different friction conditions at the interface porthole die/EN AW-6060.

Table 1. Results of the simulation with different friction models and parameters

Friction coefficient	Extrusion force [MN]	Temperature [°C]
m = f(T,P)*	7.5	598
m = 0.7	6.5	532
m = 0.1	4.3	520
µ = 0.1	6.8	532
µ = 0.05	6.3	520

*f(T,P) is the temperature and pressure dependent friction model

Fig. 6a shows the corresponding extrusion force and Fig. 6b the maximal profile exit temperature. It can be noticed that the temperature and pressure dependent friction model leads to the highest extrusion force and a temperature increase of over 13% compared to the other friction conditions.

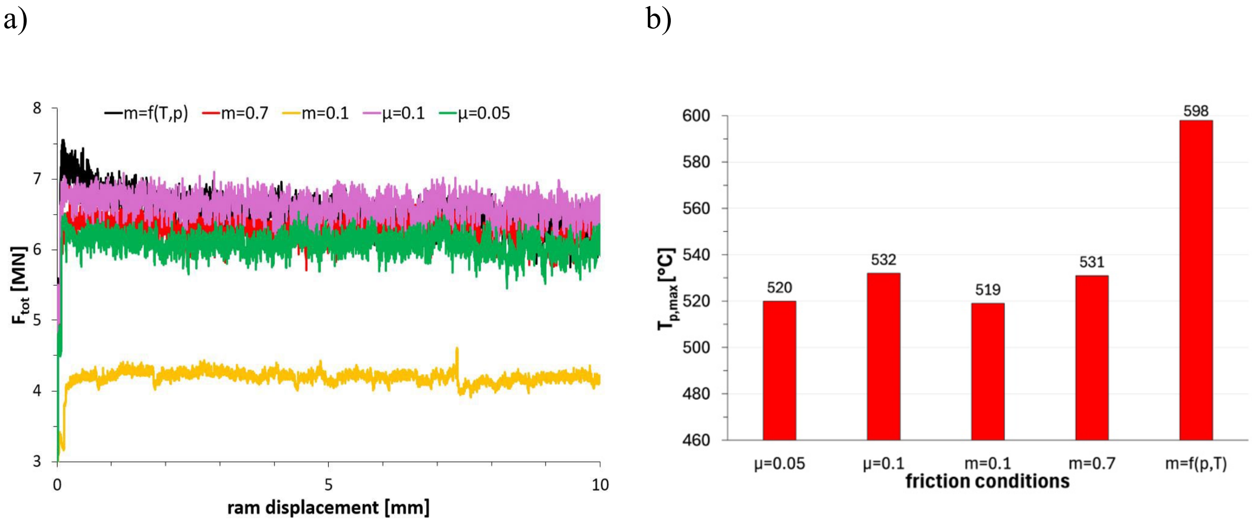

Fig. 6. Effect of different friction conditions between billet material and porthole die in FEA on a) extrusion forces b) maximal profile exit temperatures

Fig. 7 shows the distributions of material flow velocities as well as temperatures across a section view for the two friction conditions of m=0.7 and m=0.1. The velocity illustrations on top show the reduction of the dead metal zone (blue zones) in the welding chamber, whereas the temperature reduction can be seen on the bottom.

From these results it can be concluded that reduction of die friction e.g. through sonication leads to an improved material flow within the die as more billet material participates on metal flow. Additionally, the die exit temperatures can be reduced by lowering the die friction. This means that at same billet temperature, higher ram speeds and thus higher productivity could be achieved when die friction is reduced.

Furthermore, simulation results show extrusion forces lower than the providable 8.2 MN extrusion press at FZS so that extrusion trials with the selected die under the assumed boundary conditions should be feasible. Thus, modification of the pre-existing die was initiated, and the ultrasonic setup was analyzed.

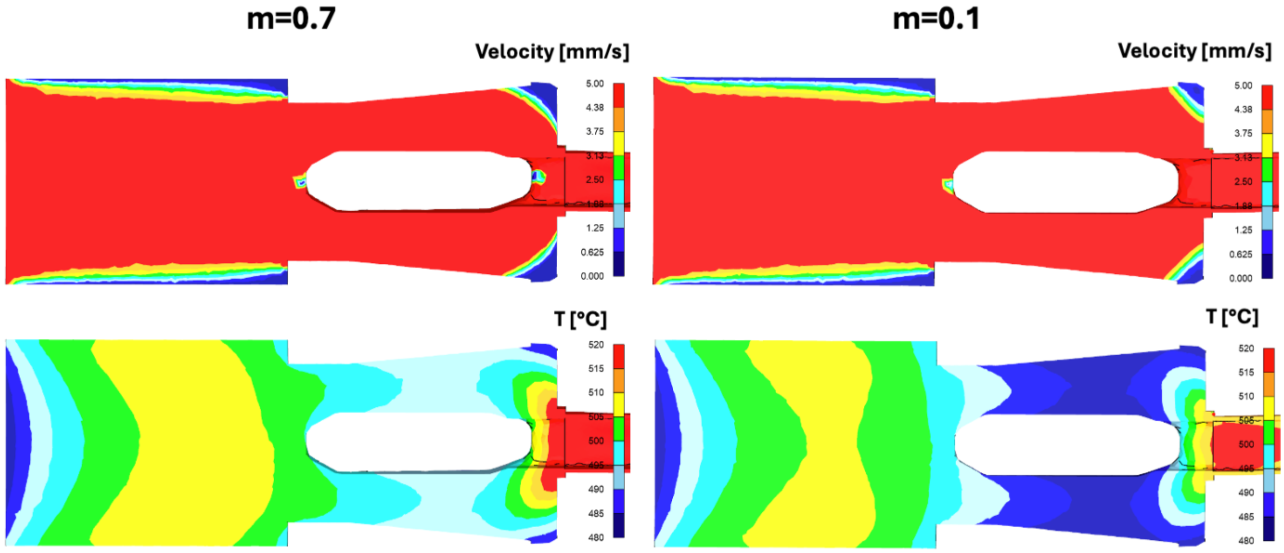

Fig. 7. Effect of different friction conditions between billet material and porthole die on distribution of flow velocities and temperatures

The modified die was simulated with an eigenmode analysis as described above. Fig. 8a shows the standardized average amplitudes of the sonotrode area per position with respect to their maximum amplitude of the specific eigenmode. Due to the arbitrary amplitude explained above, no color legend was used in Fig. 8b and Fig. 8c. Blue zones are without, red zones have a high displacement. Grey areas represent the considered positions based on Fig. 8a. Modes exhibiting high vibration amplitudes at these interfaces are considered suitable for ultrasonic excitation at the corresponding positions.

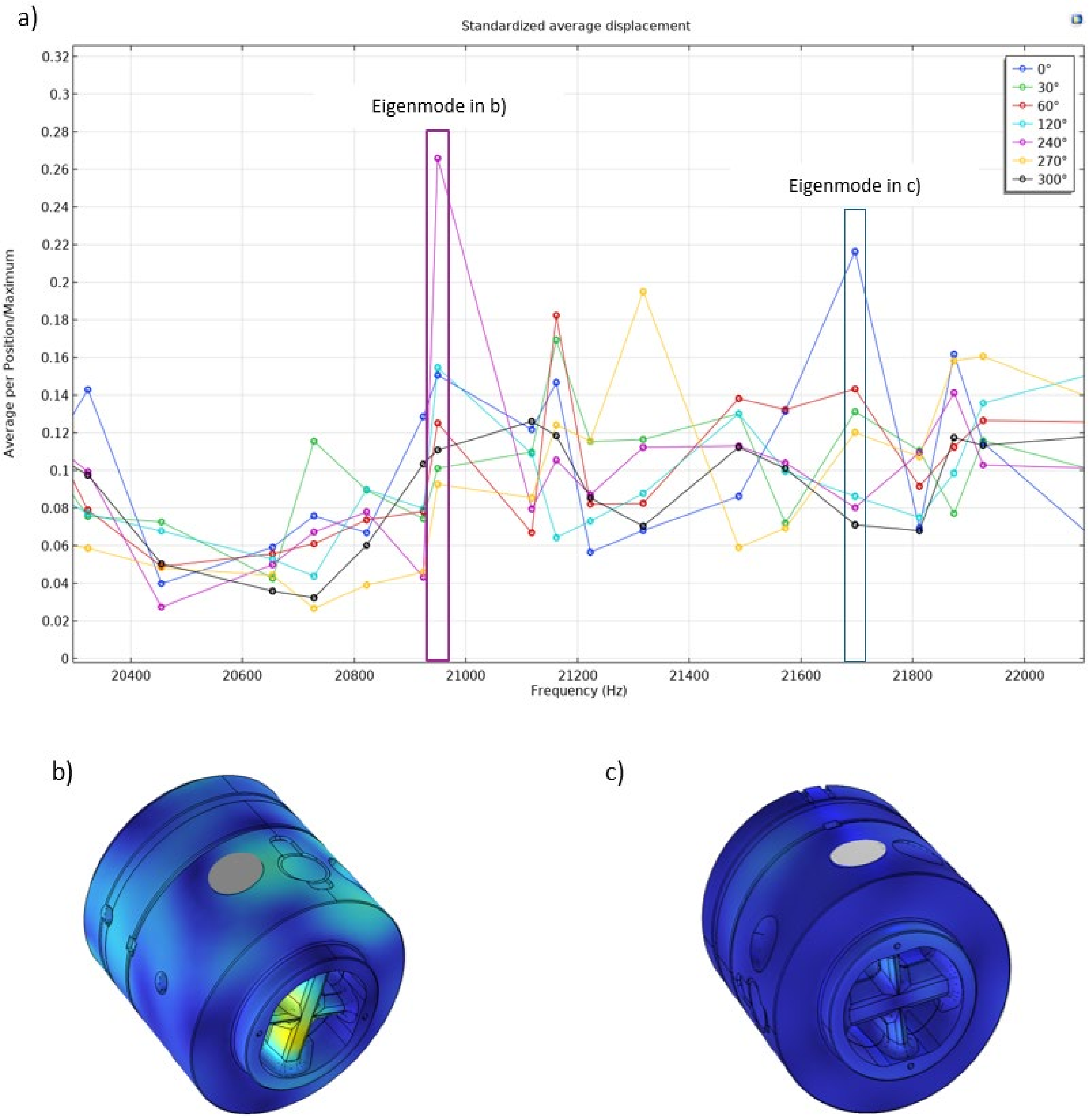

Fig. 8. Ultrasonic Simulation Results a) overview of standardized average displacement per position free configuration b) displacement at position 240°, f=20921 Hz c) displacement at position 0°. f=21709 Hz

The setup displayed in Fig. 9 is a first stage of experiments. The porthole die was placed onto a vibration insulation mat and the sonication system described above was attached to die. Different vibration frequencies were generated at varying positions. With a laser vibrometer type Keyence LK - H057 the resulting die oscillations were measured to determine the frequencies and die positions that lead to the most effective die vibrations. Additionally, a digital gauge was applied for measuring maximal displacement amplitude.

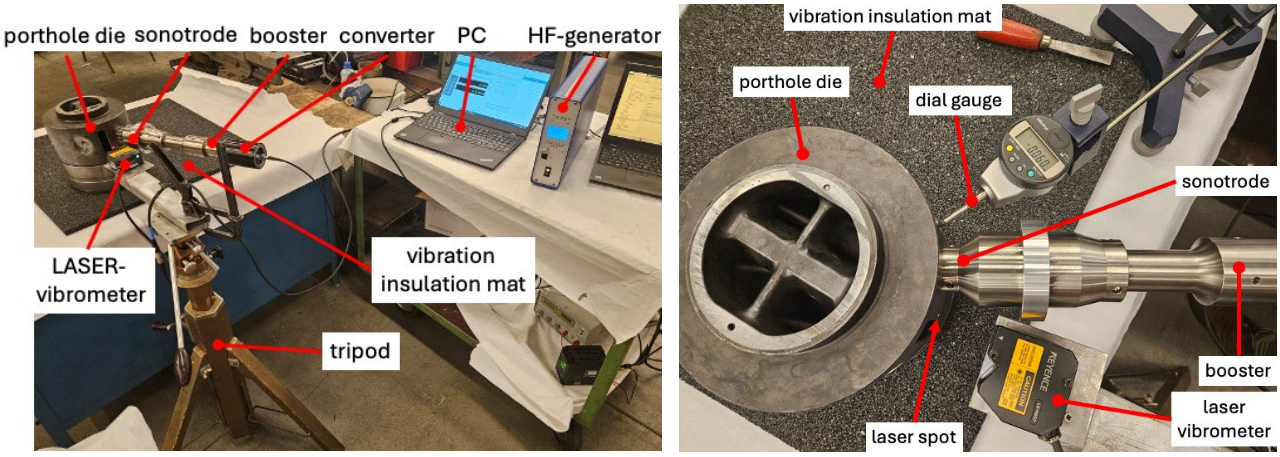

Fig. 9. Setup for high-frequency die vibration excitation and measurement of resulting die oscillation

Within the first stage of trials (Fig. 9) frequencies between 20-23 kHz and different positions in accordance with the COMSOL simulation results confirm the effective transfer of ultrasonic energy from the sonotrode into the extrusion die. The ultrasonication system's software is designed to search for a high resonance frequency by increasing the frequency. Based on the generator output power and laser vibrometer measurements, it was verified that the die is capable of absorbing and transmitting vibrations, with excitation frequencies selected near the identified resonance peaks.

The time-domain signals were transformed into the frequency domain using Fast Fourier Transform (FFT), enabling a direct comparison between the measured vibration frequencies and the sonotrode excitation frequency as shown in Fig. 10. Repeated measurements at 22 kHz showed highly consistent FFT results, demonstrating good reproducibility. Furthermore, the successful transmission of high-frequency vibrations through the die was confirmed by measurements at different locations of the tool.

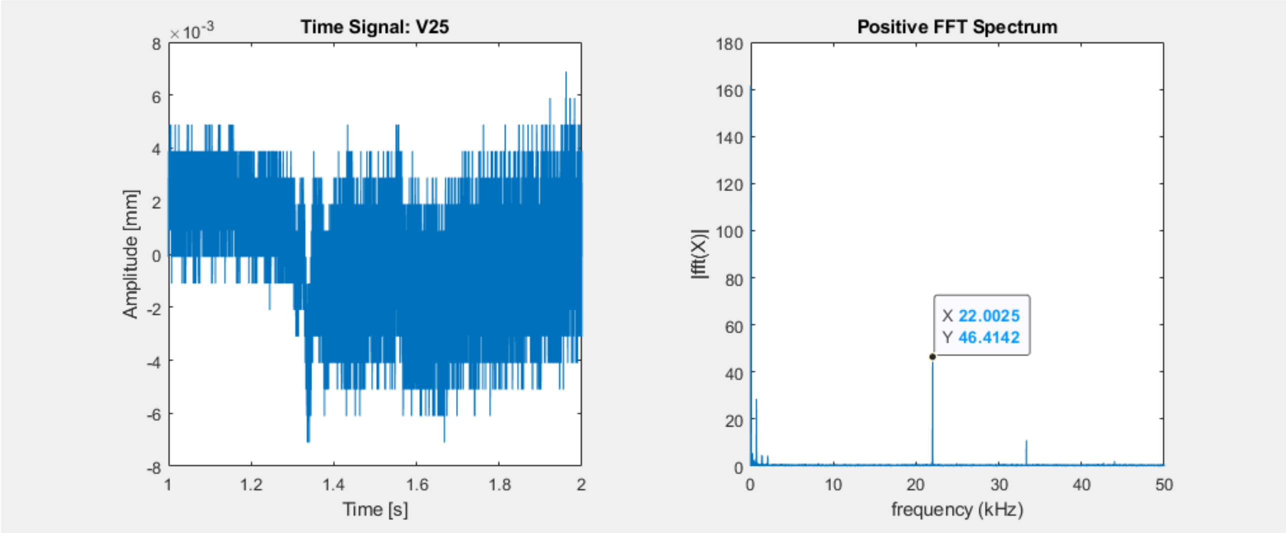

Fig. 10. 0°, 22 kHz, 50% amplitude - time-domain signal and frequency spectrum

Overall, the results demonstrate the fundamental feasibility and functional performance of high-frequency ultrasonic excitation of an extrusion die using the developed approach. The repeated measurements give the opportunity to adapt the eigenmode simulation. Based on this modal analysis, selected excitation-position combinations will be subjected to harmonic response simulations in the frequency domain. With particular attention to the vibration amplitudes within the internal flow channels, as these regions are of primary interest for reducing friction during extrusion. A high average displacement amplitude in the flow channels indicates pronounced oscillatory motion and therefore promising candidates for experimental implementation. These findings provide a targeted basis for selecting excitation parameters in subsequent physical trials.

Fig. 11a presents the final experimental setup including the modified porthole die as well as the sonication system mounted in the extrusion press. Fig. 11b displays the setup for hot condition. In order to prevent significant die cooling, porthole die is covered with a heating jacket. If the sonotrode would reach temperatures above 190 °C (Curie temperature), it would stop functioning and thus sonication would not be possible. Thus, the sonication system is protected against container heat (T_C=500 °C) by an 8 cm thick thermal insulation that is placed between container and sonication components.

Extrusion experiments applying the setup given in Fig. 11 will be conducted soon. The extrusion process without and with sonication will be characterized as well as the extruded products. Therefore, process parameters such as extrusion force and profile exit temperature will be measured and evaluated to quantify the effect of ultrasonic die sonication. The extruded profiles will subsequently be analyzed with respect to microstructural evolution and mechanical properties.

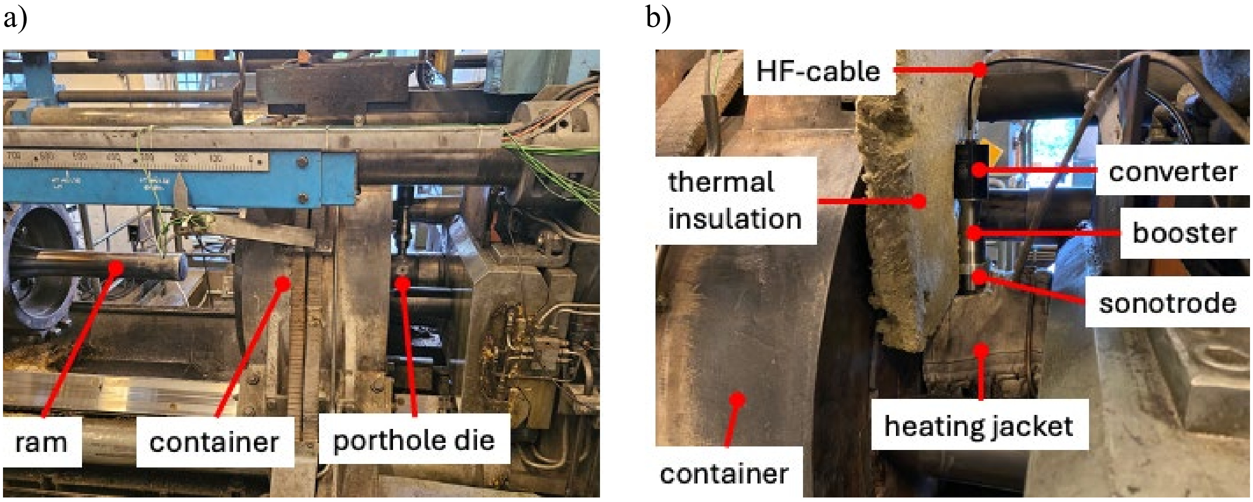

Fig. 11. Experimental setup for extrusion trials with die sonication system on 8.2 MN extrusion press of FZS TU Berlin a) general setup and b) setup with insulation and heating jacket

Summary

In this study an applicable die sonication system was applied to a porthole die to investigate the effect of ultrasonic die oscillations during extrusion of aluminum hollow profiles. The following conclusions can be drawn:

- Simulated extrusion forces indicate feasibility of extrusion trials on local extrusion press.
- FEM results indicate a trend towards reduced extrusion force and temperature, as well as improved material flow when die friction is reduced through sonication.
- Excitation frequencies were identified and were confirmed through pre-trials for selected positions.
- The die sonication system was implemented, approved, and is now available for upcoming experimental trials.

Acknowledgement

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