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Investigation on friction characteristics of micro double cup extrusion assisted by different ultrasonic vibration modes

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Abstract: Ultrasonic assisted plastic micro-forming is a research hotspot in metal forming process. The friction characteristic is a key factor affecting the micro-forming properties of metal in ultrasonic assisted micro-forming process. However, the existed researches were mostly focused on the friction characteristics of free surfaces, while few were studied on the friction characteristics between sample and mold cavity. In this paper, the micro double cup extrusion experiments of copper T2 were conducted to investigate the friction characteristics between sample and mold cavity with multiple ultrasonic vibration modes. Furthermore, the numerical model was developed to quantify the friction stress reduction caused by multiple ultrasonic vibration modes and estimate its contribution to decreasing the forming stress, which was usually considered mainly affected by acoustic softening, stress superposition and friction reduction. The results show that the forming stress and the surface roughness of extruded samples are decreased sequentially with the multiple ultrasonic vibration modes of tool vibration (TV), workpiece vibration (WV) and compound vibration (CV). The cup height ratios of double cup extrusion are also increased sequentially with the ultrasonic vibration modes. But the increase of cup height ratio does not indicate the increase of friction coefficient. The friction stress reduction between sample and mold cavity is increased sequentially with TV, CV and WV modes, and its contribution to decreasing the forming stress is 48%, 15% and 49%, respectively.

Keywords: Friction characteristics, ultrasonic vibration mode, micro double cup extrusion, copper T2

1. Introduction

Recently, micro-forming process (MFP) is widely used in medical devices, communication devices, micro-electro mechanical system (MEMS) and other fields, depending on its advantages of simple process, high efficiency, excellent performance, high precision and low manufacturing cost [1]. With the increased demand for MFP, the conventional MFP was unable to satisfy the key challenges of size effect and micro-formability of high-strength materials [2]. The ultrasonic vibration assisted micro-forming (UVAMF) technology has been developed to improve size accuracy and formability of micro components [3]. However, the description of friction characteristics between sample and mold cavity is still a fundamental problem in all micro-forming processes, especially in UVAMF, which possesses an important research value [4].

The experiments such as ring compression and forward or double cup extrusion were often used to study the friction behavior in MFP [5]. Ebrahimi et al. estimated the constant friction coefficient by cold/hot ring compression experiments [6]. Han et al. proposed an effective three-dimensional elastoplastic dynamic explicit finite element model to reveal the friction behavior of circular specimen in the cold rotary forging process [7]. Krishnan et al. compared experimental results of micro forward extrusion of brass with finite element simulations, and then directly measured the friction coefficient by micro-pin size [8]. Buschhausen et al. proposed a double-cup extrusion (DCE) method to evaluate friction and lubrication [9]. The calibration curve (cup height ratio and friction coefficient correlation curve) was established basing on finite element analysis, and the friction coefficient was quantified on the calibration curve by the experimental cup height ratio. Schrader et al. proposed a method for designing double-cup extrusion experiment that was more sensitive to friction changes based on the evaluation of double-cup extrusion [10]. Kim et al. evaluated frictional characteristics by double-cup and spike forging experiments [11]. The friction coefficients were obtained by matching the cup height ratios and spike heights in the experiments and simulations. The above researches were

mostly concentrated on investigating friction behavior in MFP, and the friction behavior in UVAMF has attracted more attention in recent years.

Pohlman et al. demonstrated that the friction stress between samples and tool was decreased when the direction of ultrasonic vibration was consistent with the direction of workpiece motion [12]. Yao et al. certified that the interfacial friction between sample and tool was decreased by high-frequency ultrasonic vibration in different micro extrusion experiments [13]. Bunget et al. showed that the forming stress was reduced and the surface topography was improved by ultrasonic vibration in ultrasonic assisted micro-extrusion experiments [14]. Xie et al. discovered that interfacial friction coefficient was decreased by ultrasonic vibration in ultrasonic assisted upsetting of ring samples of 6063 aluminum alloy [15]. Shahrokh et al. evaluated the contribution of friction reduction effect and acoustic softening effect in forming stress reduction by ultrasonic assisted ring compression experiments [16]. Zha et al. developed a friction model to describe the friction reduction effect of ultrasonic vibration [17]. Lin et al. predicted the friction coefficient and frictionless stress by developing a theoretical model related to the friction coefficient, stress, and strain [18]. From the available researches, the friction behavior between sample and tool surface was mainly studied, while the friction characteristics between sample and mold cavity was rarely investigated in UVAMF.

Ultrasonic vibration-assisted double cup extrusion process was usually used to study the friction behavior between sample and mold cavity. Hung et al. suggested that the friction coefficient between sample and mold cavity would be increased in UVAMF, because the material temperature raised by ultrasonic vibration during extrusion [19]. However, Zhai et al. found that the friction coefficient between sample and mold cavity would be decreased in UVAMF while applying ultrasonic vibration on upper and lower punches at the same time [20].

According to the above research results, the ultrasonic vibration should make an opposite effect on the friction coefficient between sample and mold cavity. The reason is that the friction coefficients in these papers were all calibrated by comparing cup height ratio of double cup extrusion with the simulation results, which cannot reflect the ultrasonic softening effect of ultrasonic vibration in UVAMF comprehensively. The simulation results of UVAMF can only simulate the ultrasonic stress superposition effect by setting high frequency load, while the ultrasonic softening effect of material cannot be reflected at the same time [21]. So the ultrasonic friction mechanism between sample and mold cavity in UVAMF should be made further analyzed and quantitative description.

To investigate the friction characteristics between sample and mold cavity in UVAMF, the micro double cup extrusion (MDCE) experiments of copper T2 with multiple ultrasonic vibration modes (tool vibration (TV), workpiece vibration (WV) and tool-workpiece composite vibration (CV)) were applied in this paper. Its formability (forming stress, cup height) and friction characteristics (cup height ratio, surface roughness) were analyzed. In addition, a quantitative description method was proposed to describe the friction reduction effect of ultrasonic vibration and its contribution to decreasing the forming stress. This study should be helpful for further investigating the mechanism of friction reduction effect in UVAMF.

2. Experimental process

2.1. Experimental setup

The ultrasonic assisted MDCE experiments were performed with a compound ultrasonic vibration system, as shown in Fig.1(a). The system was consisted by a 10 kN precision micro-forming press, two ultrasonic vibration platforms, two 20 kHz ultrasonic generators, tools, mold components and data collection module [22]. The ultrasonic vibration platform was composed of two ultrasonic transducers, two ultrasonic step horns, and a specially designed porous sonotrode, which were horizontally connected in series via double end studs and supporting bases, as depicted in Fig.1(b). The tool and mold were fixed on the center of the platform to realize multiple ultrasonic vibration modes, as depicted in Fig.1(c). The data collection module was composed of displacement sensor and pressure sensor.

Figure 1. The structure and photos of (a) compound ultrasonic vibration assisted micro-extrusion system and (b) ultrasonic vibration platform (c) tool and mold/workpiece installed on the platforms.

2.2. Material and Mold

Due to good formability of copper T2, it was chosen as the samples material, and its chemical composition is listed in Table 1. Before experiments, in order to obtain grain sizes (L) of 21 μm , the copper wire was conducted by annealing in furnace at 600 $^{\circ}\text{C}$ for 12 h. The microstructure of the heat-treated copper T2 is shown in Fig.2(a), and it was cut into cylindrical samples with $\phi 2 \times 2$ mm by wire-cut and grinding machine, as shown in Fig.2(b). The mold components were composed of upper plate, lower plate, tool head and collar, as shown in Fig.3(a, b). The center of upper plate had a $\phi 2$ mm through hole to place the blank. The center of lower plate had a static punch with a diameter of 1.2 mm and a height of 2 mm. The diameter of tool head was also set as 1.2 mm. The upper cup height ($H1$) and the lower cup height ($H2$) were formed by extrusion of tool head and static punch, respectively, as shown in Fig.3(a). The frequencies of the ultrasonic vibration platform with tool and mold analyzed by finite element methods were 19,956 Hz and 20,177 Hz, respectively, which were within the range of ultrasonic generation ($20 \text{ kHz} \pm 0.5 \text{ kHz}$), and shown in Fig.3(c, d).

Table 1. The chemical composition of copper T2 (wt.%).

Cu	Fe	S	Pb	As	Sb
≥ 99.9	≤ 0.005	≤ 0.005	≤ 0.005	≤ 0.002	≤ 0.002

Figure 2. Microstructure and sample size of heat-treated copper T2.

Figure 3. The schematic diagram and mold structure of MDCE (a, b) and modal analysis simulations (c, d).

2.3. Experimental Procedure

To achieve multiple ultrasonic vibration modes, two same ultrasonic generators were started individually or simultaneously. The ultrasonic frequency of generators was set as 19.7 kHz and the output power was adjusted (0-100%) to achieve similar amplitude of tool and mold. The amplitudes of tool or mold without load were measured with the LK-H020 laser displacement sensor of Keyence Japan. The selected amplitudes with multiple ultrasonic vibration modes and experimental parameters are expressed in Table 2.

Table 2. Experimental parameters of ultrasonic-assisted MDCE process.

Extrusion speed (mm/min)	Extrusion stroke (mm)	Ultrasonic vibration amplitude (μm)	Sample size (mm)	Lubrication condition
0.5	1	10	$\phi 2 \times 2$	Dry friction

The MDCE experiments were conducted at room temperature of 20 °C. Firstly, the tool and mold were fixed to the center of the ultrasonic vibration platform by threads. And the copper T2 sample was placed in the mold cavity and applied a preload of 40 N by the tool. Then, the ultrasonic vibration generators were activated and the tool or workpiece was vibrated together with the platforms. Meanwhile, the tool started to compress the sample with a speed of 0.5 mm/min for a stroke of 1 mm. In order to ensure the accuracy of the experiment results, each experiment was repeated at least five times.

The formability of copper T2 with multiple ultrasonic vibration modes was evaluated by forming stress and cup heights. The friction characteristics between sample and mold cavity were evaluated by the cup height ratio ($R=H1/H2$), which was the ratio of the upper cup height to lower cup height [23]. The surface topography and cup heights of extruded copper T2 samples were obtained by VHX-6000 electron microscope of Keyence, Japan. The temperatures of tool and mold with multiple ultrasonic vibration modes were obtained by MAG62 thermal imaging camera of Magnity, China.

3. Results and Discussions

3.1. Forming stress with multiple ultrasonic vibration modes

The true stress-strain curves of MDCE with multiple ultrasonic vibration modes are shown in Fig.4(a), when the ultrasonic amplitudes of tool and mold were both 10 μm . It is seen that the forming stresses were decreased sequentially with TV, WV and CV modes. And the maximum forming stress was reduced from 1691.44 MPa to 1551.54 MPa with TV, which was decreased by 139.90 MPa (8.27%) compared with static extrusion. Similarly, the maximum forming stresses with WV and CV were also decreased by 267.12 (15.79%) and 469.50 MPa (27.76%) compared with static extrusion, respectively.

The results of the upper and lower cup heights with multiple ultrasonic vibration modes are shown in Fig.4(b, c). It is shown that the values of $H1$ and $H2$ were both increased sequentially with TV, WV and CV modes, and the value of $H1$ was increased from 575 μm to 631 μm with TV, which was increased by 56 μm (9.74%) compared with static extrusion. The values of $H1$ with WV and CV were also increased by 84 μm (14.61%) and 181 μm (31.48%) compared with TV. In addition, it is also found that the increase value of $H2$ was smaller than that of $H1$ with all ultrasonic vibration modes, as shown in Fig.4(b). The maximum increase value of $H1$ was 181 μm with CV, and that of $H2$ was 48 μm , which was increased by 31.48% and 16.56% compared with static extrusion, respectively.

In the experiments, the temperature fields with multiple ultrasonic vibration modes during the forming process are shown in Fig.5, when the ultrasonic amplitudes are all 10 μm . It is seen that the temperature was the highest with WV. And the highest temperature of mold was 55.9 $^{\circ}\text{C}$, which was increased by 14.5 $^{\circ}\text{C}$ compared with static extrusion, while the temperature of tool was almost same. The elevated temperatures caused by ultrasonic vibration were not sufficient to cause a significant decrease in forming stress in the experiments [24]. Thus, the effect of thermal softening effect on forming stress was negligible in the experiments.

Figure 4. The true stress-strain curves and extrusion cup heights with multiple ultrasonic vibration modes in MDCE: (a) True stress-strain curves, (b) Extrusion cup heights, (c) Section of extruded samples.

Figure 5. Temperatures distribution of tool and mold with multiple ultrasonic vibration modes during the MDCE.

3.2. Friction characteristics with multiple ultrasonic vibration modes

The results of the cup height ratio with multiple ultrasonic vibration modes are shown in Fig.6. The cup height ratio was increased sequentially with TV, WV and CV modes. It is seen that cup height ratio was 2.03 with TV mode, which was increased by 0.05 compared with static extrusion. The cup height ratio with WV and CV were also increased by 0.08 and 0.25 compared to static extrusion, respectively.

Figure 6. The cup height ratio of the extruded samples with multiple ultrasonic vibration modes in the MDCE.

3.3. Surface topography with multiple ultrasonic vibration modes

The surface roughness R_a and surface topography at the side surface of the extruded samples with multiple ultrasonic vibration modes are shown in Fig.7 and Fig.8. It is seen that the surface roughness was decreased sequentially with static extrusion, TV, WV and CV. The surface roughness was decreased from $0.86 \mu\text{m}$ to $0.54 \mu\text{m}$ with static extrusion, which was further decreased to $0.53 \mu\text{m}$, $0.50 \mu\text{m}$ and $0.48 \mu\text{m}$ with TV, WV and CV, respectively.

It is also shown that the surface topography had obvious scratches and pits with static extrusion. When TV was applied, the surface flatness of extruded samples became smaller. When WV and CV were applied, the surface of extruded samples became smoother, and the scratches and pits became shallower. In general, the surface topography is effectively improved by ultrasonic vibration.

Figure 7. The surface roughness of extruded samples with multiple ultrasonic vibration modes.

Figure 8. The surface topography of the extruded samples with multiple ultrasonic vibration modes.

3.4. Discussions

The above experimental results showed that the formability and friction characteristics of copper T2 samples were improved by multiple ultrasonic vibration modes assisted MDCE experiments. Specifically, the forming stress and surface roughness were decreased, the cup heights and cup height ratio were increased, and the surface topography was improved. These phenomena can be explained by the ultrasonic softening, stress superposition, friction reduction and ultrasonic energy transfer capability [25].

3.4.1. Ultrasonic softening effect

It was found that the forming stress was decreased sequentially with TV, WV and CV modes. The phenomena can be explained by the ultrasonic energy transfer capability. The ultrasonic softening model relating to the ultrasonic energy density is as follows[26].

$$\sigma_{so} = -\beta M \hat{\tau} \left(E / \hat{\tau} \right)^m$$

where $\hat{\tau}$ is mechanical threshold, M is the Taylor factor, E is the ultrasonic energy density. β and m are parameters to be determined in experiments. According to the ultrasonic softening model, the forming stress reduction by ultrasonic softening is increased with the increase of ultrasonic energy. Han et al. found that the ultrasonic energy transferred to samples was increased sequentially with TV, WV and CV modes [27]. Therefore, the forming stress is decreased with multiple ultrasonic vibration modes and the CV get the maximum forming stress drop.

3.4.2. The influence mechanism of surface topography

It was found that the surface roughness was decreased sequentially with TV, WV and CV modes. And the surface topography of extruded samples was improved with multiple ultrasonic vibration modes. The main reason is that the surface of samples is polished by the mold cavity, and the relative movement between the sample and the mold cavity is increased with ultrasonic vibration. Another reason is that the high frequency movement between sample and mold with all ultrasonic vibration modes.

On the other hand, it was found that the surface topography of the extruded samples with WV and CV was smoother than that of TV. The reason is that the ultrasonic energy of CV and WV is higher than that of TV. The higher the ultrasonic energy, the stronger the acoustic softening effect [28]. Therefore, the plastic properties is improved as the acoustic softening effect is enhanced. Another reason is that the relative motion frequency between sample and mold cavity is increased with CV. As a result, the surface is polished smoother attributed to the higher material plasticity and vibration frequency with CV.

3.4.3. Friction reduction effect

According to the principle of double cup extrusion testing, if the friction coefficient between sample and mold cavity is zero, the upper cup height should be the same as the lower cup height ($H1=H2$), and the cup height ratio of the extruded samples is 1. The upper cup height is higher than the lower cup height due to the friction between sample and mold cavity in this paper.

The friction coefficient was usually obtained by aligning the cup height ratio of experiment with the friction coefficient curve of simulation in DCE [9]. Hung and Zhai et al. also used this method to obtain friction coefficient in ultrasonic assisted DCE [19,20]. In this paper, it was found that the extruded cup heights and cup height ratio of ultrasonic assisted MDCE were increased sequentially with TV, WV and CV in section 3.2, which can be explained with the acoustic softening and stress superposition effects of ultrasonic vibration. However, the simulation process of UVAMF can only reflect the stress superposition effect by setting high frequency load, while the acoustic softening effect cannot be simulated [21]. Therefore, the friction coefficient deduced by simulation was inaccurate with the results of ultrasonic assisted MDCE. And the friction reduction effect of different ultrasonic vibration modes cannot be explained by the simulation results, which should be made quantitatively description by numerical model.

3.4.4. Model development for friction reduction effect

Until now, the quantitative description of action mechanism for ultrasonic energy field has become the key problem of special energy field assisted plastic forming process [1]. According to the above, the cup height ratio was increased, while the surface roughness was decreased with multiple ultrasonic vibration modes. The increase in cup height ratio does not indicate an increase in the friction coefficient in this experiment. Therefore, in this study, it is tried to develop a numerical model to quantify the friction reduction effect of multiple ultrasonic vibration modes. According to the schematic diagram of multiple ultrasonic vibration modes assisted MDCE, as shown in Fig.9, the stress equilibrium equation in the axial direction can be formulated as follows.

$$\sigma_{s1} - \tau_{f1} - \tau_{f3} = \sigma_{s2} - \tau_{f2} \quad (1)$$

Where σ_{s1} is the positive extrusion stress, σ_{s2} is the reverse extrusion stress, τ_{f1} and τ_{f2} are the friction stress between the side surfaces of upper and lower punches and sample, respectively, and τ_{f3} is the friction stress between sample and mold cavity.

Figure 9. Schematic diagram of MDCE with multiple ultrasonic vibration modes.

This study belongs to the category of micro-forming, so the ultrasonic energy transferred to top and bottom of sample is considered to be the same. The diameters of upper and lower punches, and the surface roughness of top and bottom surfaces of sample are same. Therefore, the plastic forming process of the upper and lower cups is assumed to be the same [23]. Thus, the friction stress between sample and upper punch (τ_{f1}), and lower punch (τ_{f2}) are considered equal ($\tau_{f1} = \tau_{f2}$) and Eq.(1) can be changed as follows.

$$\tau_{f3} = \sigma_{s1} - \sigma_{s2} \quad (2)$$

According to the above assumption, the stress-strain curve of upper cup is used as a calibration curve to obtain the forming stress of lower cup. Firstly, it is tried to describe the true stress-strain curves of the upper and lower cup forming processes simultaneously with a power strengthening model $\sigma_s = k(\varepsilon)^n$, where k is the strength coefficient, n is the strain hardening index, σ_s and ε are the true stress and strain respectively [29]. Therefore, the true stress-strain curve of the upper cup forming process can be written as follows.

$$\sigma_{s1} = k(\varepsilon_1)^n \quad (3)$$

where σ_{s1} and ε_1 are the true stress and strain of the upper cup forming process, respectively. The strength coefficients, strain hardening indices and maximum strains with multiple ultrasonic vibration modes were obtained from the data in Fig.4(a), as listed in Table 3.

Table 3. The parameters of calibration curves with multiple ultrasonic vibration modes.

	Strength coefficient k	Strain hardening index n	Maximum strain ε_1
Static extrusion	3736.29	0.85	0.3936
Tool vibration	3315.32	0.81	0.3916
Workpiece vibration	2883.81	0.78	0.4048
Compound vibration	3017.88	1.00	0.4049

The strain of lower cup forming process is obtained by the ratio of lower cup height to upper cup height with multiple ultrasonic vibration modes, as follows.

$$\varepsilon_2 = (H2/H1)\varepsilon_1 \quad (4)$$

where ε_2 is the strain of lower cup forming process. According to Eq.(3) and Eq.(4), the stress of lower cup forming process is obtained from its strain on the calibration curve, which is calculated as follows.

$$\sigma_{s2} = k[(H2/H1)\varepsilon_1]^n \quad (5)$$

where σ_{s2} is the stress of lower cup forming process. According to Eq.(3) and Eq.(5), the difference between the forming stresses of upper and lower cups is the friction stress between sample and mold cavity, which is calculated as follows.

$$\tau_{f3} = \sigma_{s1} - \sigma_{s2} = k(\varepsilon_1)^n [1 - (H2/H1)^n] \quad (6)$$

According to Eq.(6), the friction stress between sample and mold cavity is calculated with multiple ultrasonic vibration modes, as listed in Table 4. The friction reduction stress caused by ultrasonic vibration is obtained by the difference between friction stress in multiple ultrasonic vibration modes and friction stress in static extrusion. And its contribution is obtained by the ratio of friction stress reduction to forming stress reduction with multiple ultrasonic vibration modes. As an example, the calculation method of friction stress reduction with TV is as follows.

$$\Delta\tau_{f3t} = \tau_{f3s} - \tau_{f3t} \quad (7)$$

where $\Delta\tau_{f3t}$ is the friction stress reduction between sample and mold cavity with TV, τ_{f3s} is the friction stress between sample and mold cavity in static extrusion. τ_{f3t} is the friction stress between sample and mold cavity with TV mode.

Table 4. Equations for calculating friction stress with multiple ultrasonic vibration modes.

	Equations
Static extrusion	$\tau_{f3} = 1691.37[1 - (H2/H1)^{0.85}]$
Tool vibration	$\tau_{f3} = 1551.42[1 - (H2/H1)^{0.81}]$
Workpiece vibration	$\tau_{f3} = 1424.34[1 - (H2/H1)^{0.78}]$
Compound vibration	$\tau_{f3} = 1221.94[1 - (H2/H1)]$

According to Eq.(7), the friction reduction stress between sample and mold cavity are 67.01 MPa, 130.64 MPa, 70.54 MPa with TV, WV and CV modes, respectively. And its contribution to decreasing the forming stress is 48%, 49%, and 15%, respectively, as shown in the Fig.10.

Figure 10. Frictional stress reduction and its contribution to decreasing the forming stress with multiple ultrasonic vibration modes.

The theoretical results show that the friction stress reduction between sample and mold cavity is increased sequentially with TV, CV and WV modes. The contribution value of the friction reduction effect in forming stress reduction with CV is smaller than that of TV and WV. The reason is that the ultrasonic energy of the CV is an effective superposition of TV and WV. The volume effect is the main role in forming stress reduction with CV modes.

4. Conclusions

In this study, the influences of TV, WV and CV modes on the friction characteristics and formability of copper T2 micro double cup extrusion were investigated. And the method to quantify the frictional behavior in UVAMF is proposed. The main conclusions are as follows:

(1) The forming stress and surface roughness were decreased sequentially with TV, WV and CV modes compared with static extrusion, while the formability and surface topography were improved. The forming stress under CV was decreased by 469.5 MPa (27.76%) compared with static extrusion. The surface roughness with CV was decreased by 0.06 μm (12.5%) compared with static extrusion. While the upper and lower cup heights with CV were increased by 181 μm (31.48%) and 48 μm (16.55%) compared with static extrusion, respectively.

(2) The cup height ratios were increased sequentially with TV, WV and CV modes in ultrasonic assisted MDCE experiments. However, the change rule of cup height ratio is not consistent with that of friction coefficient due to the acoustic softening and stress superposition effects of ultrasonic vibration. And the simulation results only reflect stress superposition effect, without acoustic softening effect. So the friction coefficient deduced by simulation was inaccurate in ultrasonic assisted MDCE.

(3) A numerical model was developed to quantify the friction reduction effect between sample and mold cavity, which could estimate its contribution value to the forming stress reduction. The results showed that the friction stress between sample and mold cavity was decreased sequentially with TV, CV and WV modes. The friction reduction stress was 67.01 MPa, 70.54 MPa, 130.64 MPa and its contribution to decreasing the forming stress was 48%, 15% and 49%, respectively.

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References

- [1] Xu J, Wang X, Wang C, Yuan L, Chen W, Bao J, et al. A Review on Micro/Nanoforming to Fabricate 3D Metallic Structures. *Adv Mater* 2020. <https://doi.org/10.1002/adma.202000893>.
- [2] Fu MW, Wang JL. Size effects in multi-scale materials processing and manufacturing. *Int J Mach Tools Manuf* 2021;167. <https://doi.org/10.1016/j.ijmachtools.2021.103755>.
- [3] Hung JC, Tsai YC. Investigation of the effects of ultrasonic vibration-assisted micro-upsetting on brass. *Mater Sci Eng A* 2013;580:125–32. <https://doi.org/10.1016/j.msea.2013.04.074>.
- [4] Fu MW, Chan WL. A review on the state-of-the-art microforming technologies. *Int J Adv Manuf Technol* 2013;67:2411–37. <https://doi.org/10.1007/s00170-012-4661-7>.
- [5] Chang CC, Huang CK. Effects of surface roughness on tribological characteristics in micro double cup extrusion of aluminum. *Key Eng Mater* 2010;419–420:5–8. <https://doi.org/10.4028/www.scientific.net/KEM.419-420.5>.
- [6] Ebrahimi R, Najafizadeh A. A new method for evaluation of friction in bulk metal forming. *J Mater Process Technol* 2004;152:136–43. <https://doi.org/10.1016/j.jmatprotec.2004.03.029>.
- [7] Han X, Hua L. Friction behaviors in cold rotary forging of 20CrMnTi alloy. *Tribol Int* 2012;55:29–39. <https://doi.org/10.1016/j.triboint.2012.05.012>.
- [8] Krishnan N, Cao J, Dohda K. Study of the size effects on friction conditions in microextrusion - Part I: Microextrusion experiments and analysis. *J Manuf Sci Eng Trans ASME* 2007;129:669–76. <https://doi.org/10.1115/1.2386207>.

- [9] Buschhausen A, Weinmann K, Lee JY, Altan T. Evaluation of lubrication and friction in cold forging using a double backward-extrusion process. *J Mater Process Tech* 1992;33:95–108. [https://doi.org/10.1016/0924-0136\(92\)90313-H](https://doi.org/10.1016/0924-0136(92)90313-H).
- [10] Schrader T, Shirgaokar M, Altan T. A critical evaluation of the double cup extrusion test for selection of cold forging lubricants. *J Mater Process Technol* 2007;189:36–44. <https://doi.org/10.1016/j.jmatprotec.2006.11.229>.
- [11] Kim JH, Ko BH, Kim JH, Lee KH, Moon YH, Ko DC. Evaluation of friction using double cup and spike forging test for dry-in-place coating and forming oils. *Tribol Int* 2020;150:106361. <https://doi.org/10.1016/j.triboint.2020.106361>.
- [12] Pohlman R, Lehfeltdt E. Influence of ultrasonic vibration on metallic friction. *Ultrasonics* 1966;4:178–85. [https://doi.org/10.1016/0041-624X\(66\)90244-7](https://doi.org/10.1016/0041-624X(66)90244-7).
- [13] Yao Z, Kim GY, Faidley L, Zou Q, Mei D, Chen Z. Experimental study of high-frequency vibration assisted micro/mesoscale forming of metallic materials. *J Manuf Sci Eng Trans ASME* 2011;133. <https://doi.org/10.1115/1.4004612>.
- [14] Bunget C, Ngaile G. Influence of ultrasonic vibration on micro-extrusion. *Ultrasonics* 2011;51:606–16. <https://doi.org/10.1016/j.ultras.2011.01.001>.
- [15] Xie Z, Guan Y, Zhu L, Zhai J, Lin J, Yu X. Investigations on the surface effect of ultrasonic vibration-assisted 6063 aluminum alloy ring upsetting. *Int J Adv Manuf Technol* 2018;96:4407–21. <https://doi.org/10.1007/s00170-018-1611-z>.
- [16] Shahrokh R, Ghaei A, Farzin M, Ahmadi F. Experimental and numerical investigation of ultrasonically assisted micro-ring compression test. *Int J Adv Manuf Technol* 2018;95:3487–95. <https://doi.org/10.1007/s00170-017-1463-y>.
- [17] Zha C, Zha S. Experimental investigation of friction based on ultrasonic vibration. *UPB Sci Bull Ser D Mech Eng* 2020;82:17–28.
- [18] Lin J, Li J, Liu T, Zhu L, Chu X, Zhao G, et al. Evaluation of friction reduction and frictionless stress in ultrasonic vibration forming process. *J Mater Process Technol* 2021;288:116881. <https://doi.org/10.1016/j.jmatprotec.2020.116881>.
- [19] Hung JC, Huang CC. Evaluation of friction in ultrasonic vibration-assisted press forging using double cup extrusion tests. *Int J Precis Eng Manuf* 2012;13:2103–8. <https://doi.org/10.1007/s12541-012-0278-x>.
- [20] Zhai J, Guan Y, Li Y, Liu Y, Lin J. The surface effect of ultrasonic vibration in double cup extrusion test. *J Mater Process Technol* 2022;299:117344. <https://doi.org/10.1016/j.jmatprotec.2021.117344>.
- [21] Yao Z, Kim GY, Faidley L, Zou Q, Mei D, Chen Z. Effects of superimposed high-frequency vibration on deformation of aluminum in micro/meso-scale upsetting. *J Mater Process Technol* 2012;212:640–6. <https://doi.org/10.1016/j.jmatprotec.2011.10.017>.
- [22] Han G, Peng Z, Xu L, Li N. Ultrasonic vibration facilitates the micro-formability of a Zr-based metallic glass. *Materials (Basel)* 2018;11:1–14. <https://doi.org/10.3390/ma1122568>.
- [23] Tekkaya AE, Homberg W, Brosius A. 60 Excellent inventions in metal forming. 2015. <https://doi.org/10.1007/978-3-662-46312-3>.
- [24] Liu T, Lin J, Guan Y, Xie Z, Zhu L, Zhai J. Effects of ultrasonic vibration on the compression of pure titanium. *Ultrasonics* 2018;89:26–33. <https://doi.org/10.1016/j.ultras.2018.04.006>.
- [25] Sedaghat H, Xu W, Zhang L. Ultrasonic vibration-assisted metal forming: Constitutive modelling of acoustoplasticity and applications. *J Mater Process Technol* 2019;265:122–9. <https://doi.org/10.1016/j.jmatprotec.2018.10.012>.

- [26] Wang CJ, Liu Y, Guo B, Shan DB, Zhang B. Acoustic softening and stress superposition in ultrasonic vibration assisted uniaxial tension of copper foil: Experiments and modeling. *Mater Des* 2016;112:246–53. <https://doi.org/10.1016/j.matdes.2016.09.042>.
- [27] Han G, Wan W, Zhang Z, Xu L, Liu F, Zhang H. Experimental investigation into effects of different ultrasonic vibration modes in micro-extrusion process. *J Manuf Process* 2021;67:427–37. <https://doi.org/10.1016/j.jmapro.2021.05.007>.
- [28] Yao Z, Kim GY, Wang Z, Faidley LA, Zou Q, Mei D, et al. Acoustic softening and residual hardening in aluminum: Modeling and experiments. *Int J Plast* 2012;39:75–87. <https://doi.org/10.1016/j.ijplas.2012.06.003>.
- [29] Structures MB. Unified Constitutive Laws of Plastic Deformation. 1996. <https://doi.org/10.1016/b978-0-12-425970-6.x5000-0>.

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- Fig. 3. The schematic diagram and mold structure of MDCE (a, b) and modal analysis simulations (c, d).
- Fig. 4. The true stress-strain curves and extrusion cup heights with multiple ultrasonic vibration modes in MDCE: (a) True stress-strain curves, (b) Extrusion cup heights, (c) Section of extruded samples.
- Fig. 5. Temperatures distribution of tool and mold with multiple ultrasonic vibration modes during the MDCE.
- Fig. 6. The cup height ratio of the extruded samples with multiple ultrasonic vibration modes in the MDCE.
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- Fig. 8. The surface topography of the extruded samples with multiple ultrasonic vibration modes.
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Table. 1. The chemical composition of copper T2 (wt.%).

Table. 2. Experimental parameters of ultrasonic-assisted MDCE process.

Table. 3. The parameters of calibration curves with multiple ultrasonic vibration modes.

Table. 4. Equations for calculating friction stress with multiple ultrasonic vibration modes.

Table 1. The chemical composition of copper T2 (wt.%).

Cu	Fe	S	Pb	As	Sb
≥ 99.9	≤ 0.005	≤ 0.005	≤ 0.005	≤ 0.002	≤ 0.002

Table 2. Experimental parameters of ultrasonic-assisted MDCE process.

Extrusion speed (mm/min)	Extrusion stroke (mm)	Ultrasonic vibration amplitude (μm)	Sample size (mm)	Lubrication condition
0.5	1	10	$\phi 2 \times 2$	Dry friction

Table 3. The parameters of calibration curves with multiple ultrasonic vibration modes.

	Strength coefficient k	Strain hardening index n	Maximum strain ε_1
Static extrusion	3736.29	0.85	0.3936
Tool vibration	3315.32	0.81	0.3916
Workpiece vibration	2883.81	0.78	0.4048
Compound vibration	3017.88	1.00	0.4049

Table 4. Equations for calculating friction stress with multiple ultrasonic vibration modes.

Equations	
Static extrusion	$\tau_{f3} = 1691.37[1 - (H2/HI)^{0.85}]$
Tool vibration	$\tau_{f3} = 1551.42[1 - (H2/HI)^{0.81}]$
Workpiece vibration	$\tau_{f3} = 1424.34[1 - (H2/HI)^{0.78}]$
Compound vibration	$\tau_{f3} = 1221.94[1 - (H2/HI)]$