

Investigation on the mechanism of improving the forming quality of cavitation water jet micro-punching by using a rubber membrane

Fuzhu Li, Wei Meng, Stefano Mori, Yun Wang, Chunju Wang & Yuqin Guo

Abstract: Cavitation water jet micro-punching (CWJP) is a high-strain-rate micro-punching technique, which utilizes the high-energy shock waves generated by the concentrated collapse of cavitation clouds to perform metal foil micro-punching. However, some defects like brittle fracture, warpage deformation and edge tearing are inevitable in the micro-punched holes formed by the CWJP process due to the reverse impact of high-speed backflow. To solve this issue, a novel rubber membrane-assisted cavitation water jet micro-punching (RA-CWJP) technique was proposed in the present work, in which a flexible rubber membrane was introduced as a soft punch to prevent cavitation water jet from entering the die hole. The comparative experiments of the CWJP and RA-CWJP processes were carried out with 50 μ m thick T2 copper foils as the experimental material. The forming quality of micro-punched holes formed by two processes was examined in terms of microscopic morphology (fracture surface and cross-section), shape and dimensional accuracy. Additionally, the effect of backflow on the CWJP process was investigated. To better understand the improvement mechanism of rubber membrane on the forming quality of micro-punched holes, the fluid-solid coupling simulation was conducted. The research results show that applying a 200 μ m thick rubber membrane to the CWJP process can avoid the brittle fracture, warping deformation, and edge tearing of micro-punched holes caused by the reverse impact force of backflow. Meanwhile, the introduction of this rubber membrane increases the depth of the shearing zone and decreases the depth of the rollover zone, as well as the formation of burrs. Compared to the CWJP process, the shape and dimensional accuracy of micro-punched holes formed by the RA-CWJP process increased by a maximum of 63.5% and 82.2%, respectively. The excellent fluidity and compressibility of rubber membrane enable precise shearing separation of the copper foil along the die edge, and heightened shape accuracy can be achieved. Furthermore, the dimensional accuracy is significantly improved due to the substantial plastic deformation under rubber membrane compression, which reduces the amount of elastic recovery deformation after micro-punching.

Keywords: Rubber membrane; Cavitation water jet; Metal foil; Micro-punching; Forming quality

1. Introduction

With the rapid advancement of the advanced manufacturing industry, industrial products are increasingly exhibiting a trend towards integration and miniaturization. There is a growing demand

1 for metal foil components with micro-hole characteristics across numerous industrial sectors,
2 particularly in the aerospace, electronic communication, medical equipment, and vehicle industry
3 [1]. Compared to micro-electrical discharge machining (EDM), micro-ultrasonic machining (USM),
4 micro-drilling, electrochemical micro-machining, and other micro-hole fabrication processes, the
5 micro-punching process offers several advantages, such as high forming precision, high productivity,
6 and low cost [2]. However, the mechanical property and machining quality of the micro-holes are
7 profoundly influenced by size effects when the specimen dimensions are scaled down from macro
8 to micro level [3]. Presz and Rosochowski [4] reported that the grain size effect induced anisotropy
9 in material plasticity, which deteriorates the surface quality of metal formed miniature components.
10 Moreover, the investigational results provided by Tiesler [5] indicated that the friction increased
11 greatly with the reduction of specimen size. The friction size effect has great influence on loading
12 force, the behavior of contact surface between material and tools and the flow of material [6]. This
13 process also faces several challenges, including the difficulty of manufacturing a highly rigid punch
14 and the strict requirements for precise alignment between the punch tool and die [7]. These problems
15 significantly impair micro-holes' machining quality and service safety, thereby limiting the
16 industrial application of the micro-punching process [8].

17 In recent years, high-strain-rate micro-punching processes that employ high-speed, high-
18 energy transient impact loads have demonstrated significant advantages in improving the fracture
19 surface quality, machining precision, abrasion resistance, and fatigue life of micro-punched holes
20 [9]. Consequently, these innovative processing methods are regarded as promising techniques for
21 manufacturing micro-punched holes. Among these, laser shock micro-punching and
22 electromagnetic micro-punching are the two most representative high-strain-rate micro-punching
23 processes. Using a pulsed laser shock wave, a 1.2 mm diameter circular hole was successfully
24 punched in a 50 μm copper foil [10]. The fracture mechanism of the workpiece was analyzed using
25 both experimental and numerical simulation methods [11]. However, surface ablation occurs during
26 the laser shock process, and the residual ablated material on the micro-punched holes is difficult to
27 remove [12]. Furthermore, the non-uniform distribution of laser shock pressure can induce irregular
28 or uneven deformation, which adversely affects the forming quality of the micro-punched holes [13].
29 Electromagnetic micro-punching has also been utilized to fabricate circular micro-holes on a 100
30 μm thick TA1 titanium foil [14]. As discharge energy increases, the range of diameters for punchable

1 holes gradually expands [15]. However, this technique has several drawbacks. The coil wires are
2 exposed to significant electromagnetic forces, which can induce unwanted deformations that may
3 compromise the insulation layer, leading to coil failure [16]. Moreover, local overheating resulting
4 from contact arcing can cause damage to both the workpiece and the conductive channel [17].

5 Cavitation water jet micro-forming (CWJF) is a novel high-strain-rate micro-forming
6 technique for inducing plastic deformation in metal foils. It utilizes high-energy transient shock
7 waves generated by the concentrated collapse of cavitation clouds within a cavitation water jet. The
8 collapse of these cavitation clouds generates high-energy shock waves with peak amplitude pressure
9 generally ranging from 10^2 to 10^4 MPa, which is widely acknowledged by researchers [18]. To date,
10 CWJF has been successfully applied to processes such as micro-bulging and micro-punching of
11 metal foils, yielding favourable forming results. Li et al. [19] employed the CWJF process for array
12 micro-bulging of 304 stainless steel foil with a thickness of 100 μm , resulting in a formed part that
13 exhibited a uniform thickness distribution. In the same year, Li et al. [20] conducted a series of
14 cavitation water jet impact micro-bulging experiments on 100 μm thick TA2 titanium foils. They
15 found that the uniform distribution of liquid pressure led to a more uniform thickness distribution
16 in the workpiece compared to laser shock micro-forming. Yu et al. [21] also observed similar results
17 for the micro-bulging of copper foil using the CWJF process. He et al. [22] researched the plastic
18 deformation mechanism of metal foil micro-bulging in the CWJF process. Their results indicated
19 that the transient impact pressure of the cavitation water jet caused significant plastic deformation
20 in the metal foil. Moreover, as the impact time increased, the work-hardening effect of the micro-
21 bulging parts became more pronounced. Benefiting from the extensive research on the CWJF
22 process, Wang et al. [23] proposed the cavitation water jet micro-punching (CWJP) process. They
23 successfully punched regular quadrilateral, regular hexagons, and circular holes in copper foils.

24 However, a major challenge in the CWJP process is the reverse impact force caused by the
25 backflow of the cavitation water jet. During the CWJP process, the local fracture separation allows
26 the high-speed water jet to enter the die cavity when the cavitation water jet directly impacts the
27 workpiece. Consequently, the high-speed water jet strikes the bottom of the die hole, generating
28 backflow that impacts the workpiece in the direction opposite to that of cavitation water jet impact
29 force. This phenomenon can lead to brittle fracture, warpage deformation, edge tearing, and other
30 defects in the micro-punched holes, thereby seriously affecting the processing quality of these parts.

1 Additionally, the water medium remaining in the die cavity forms a “water cushion” effect, which
2 generates a local static pressure zone [24]. This weakens the high-speed impact force of the
3 cavitation water jet.

4 To address the problems mentioned above in the CWJP process, it is required to introduce an
5 intermediate medium to transmit the impact pressure of the cavitation water jet, thereby preventing
6 its entry into the die cavity. Given this, a novel rubber membrane-assisted cavitation water jet micro-
7 punching (RA-CWJP) technique is proposed in this study, in which the rubber membrane functions
8 as a force transmission medium. The primary objective of this paper is to investigate the effect of
9 the rubber membrane on the micro-punching process to improve the forming quality. To this end, a
10 series of RA-CWJP and CWJP experiments were conducted using 50 μm thick T2 copper foils as
11 the experimental material. A process window was established for the incident pressure and rubber
12 thickness. The forming quality of micro-punched formed by two processes was compared and
13 analyzed regarding microscopic morphology (fracture surface and cross-section), shape and
14 dimensional accuracy. Additionally, the effect of the backflow on the CWJP process was
15 investigated. Meanwhile, a numerical model of fluid-solid coupling was established to analyze the
16 dynamic fracture process and stress state of the copper foil, aiming to demonstrate the improvement
17 mechanism of rubber membrane on the forming quality of micro-punched holes.

18 **2. Process principle, experimental methods and material**

19 **2.1 Principle of rubber membrane-assisted cavitation water jet micro-punching process**

20 Fig. 1 presents the schematic diagram of the RA-CWJP process. As the high-speed water jet
21 passes through the submerged cavitation nozzle, the rapid increase in flow velocity creates a low-
22 pressure zone at the nozzle throat, resulting in the generation of cavitation bubbles. Subsequently,
23 the high-speed jet carrying these bubbles interacts with the surrounding static water, further forming
24 a low-pressure vortex structure and a cavitation cloud composed of numerous cavitation bubbles.
25 As the jet flows downward and the pressure gradually recovers, the cavitation cloud undergoes a
26 concentrated collapse [25]. The concentrated collapse of these cavitation bubbles on the rubber
27 membrane surface generates high-energy shock waves, which is then transmitted through the rubber
28 to perform micro-punching on the metal foil.

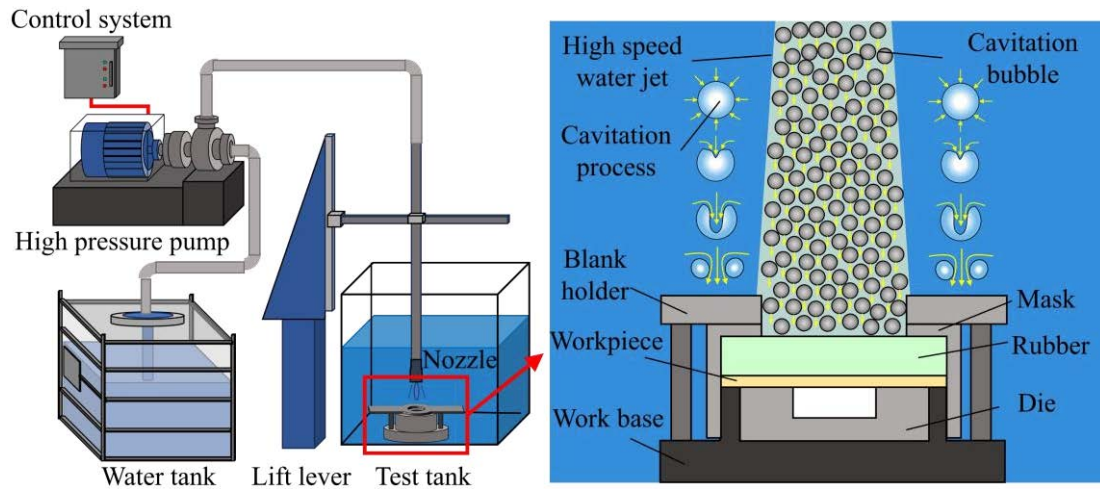


Fig. 1. Illustration of the rubber membrane-assisted cavitation water jet micro-punching process principle.

2.2 Experimental methods

The metal foil micro-punching experiment was conducted using a self-developed cavitation water jet machining system, as shown in Fig. 2. The main components of the system include a water storage tank, a TW-5570 high-pressure pump with a rated pressure of 50 MPa, a text tank fabricated from acrylic resin, a control system, a ball screw lifting mechanism, and a micro-punching experimental assembly.

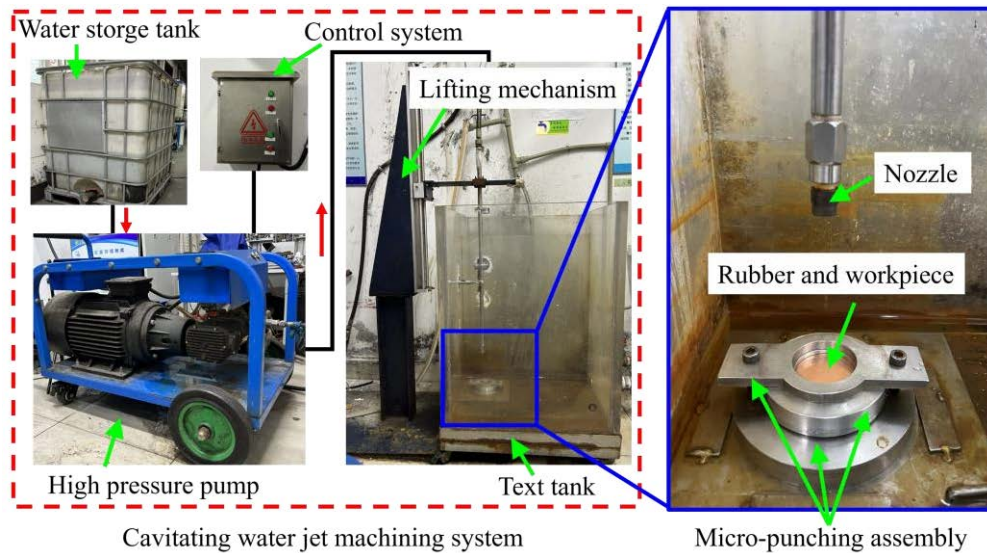


Fig. 2. Cavitation water jet machining system.

To investigate the effect of rubber on the forming quality of the micro-punched holes, a comparative experiment between the RA-CWJP and CWJP was conducted, as illustrated in Fig. 3. Fig. 3(a) displays the RA-CWJP experimental assembly, which consists of the blank holder, the

mask, the rubber membrane, and the die. Fig. 3(b) shows the CWJP experimental assembly, in which the rubber membrane is not introduced, while all other components remain the same.

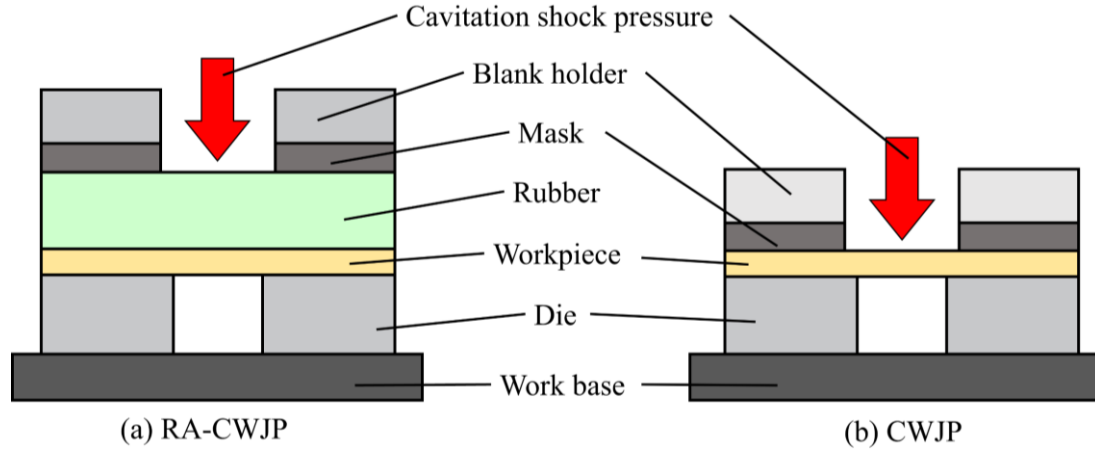


Fig. 3. Micro-punching experimental assembly of the RA-CWJP and CWJP processes.

The micro-punching experimental assembly depicted in Fig. 3 was placed at the bottom of the test tank, directly beneath the cavitation nozzle with a diameter of 1.6 mm. The incident pressure was set at three levels: 15, 20, and 25 MPa. Based on previous research [26], the standoff distance was set to 120 mm to ensure that the workpiece was positioned within the concentrated collapse range of cavitation clouds. The impact time of the experiment was set to 10 s. The mold material used was AISI 1095 high-carbon steel, which was selected for its ability to withstand the high-energy impact pressure generated by the cavitation water jet. Die holes with diameters of 1.0, 1.2, 1.4, and 1.6 mm were machined into the mold using micro-EDM. Polyurethane rubber membrane with a Shore A hardness of 70° and thicknesses of 100, 200, and 300 μm was chosen as the force transmission medium. The detailed experimental parameters are presented in Table 1.

Table 1 The detailed experimental parameters.

Parameters	Values
Incident pressure	15 MPa; 20 MPa; 25 MPa
Standoff distance	120 mm
Impact time	10 s
Nozzle diameter	1.6 mm
Thickness of polyurethane rubber	100 μm ; 200 μm ; 300 μm
Die hole diameter	1.0 mm; 1.2 mm; 1.4 mm; 1.6 mm

After the micro-punching experiment, the dimensions of the micro-punched holes were measured using a VHC-1000C ultra-depth-of-field three-dimensional microscope. Additionally, the fracture surface morphology and cross-sectional fracture morphology of these micro-punched holes

were respectively observed via a JEOL JSM-7800F field-emission scanning electron microscope and an OLYMPUS OLS5000 confocal laser scanning microscope.

2.3 Material

T2 copper foil is widely used in advanced manufacturing industries due to its excellent thermal conductivity, high ductility, and favourable mechanical properties. In this experiment, T2 copper foils with a thickness of 50 μm were employed. The foils were trimmed to dimensions of 60 $\times$ 60 mm to ensure compatibility with the experimental mold.

3. Numerical simulation

Two numerical models were established to conduct a comprehensive and multifaceted analysis of the RA-CWJP process. The first is the cavitation water jet fluid field model, which was employed to calculate the impact pressure generated by the collapse of the cavitation clouds. The second is the fluid-solid coupling model of cavitation water jet impact assisted by rubber membrane for micro-punching. This simulation was designed to elucidate the dynamic deformation and fracture mechanisms of the copper foil during the RA-CWJP process.

3.1 Cavitation water jet fluid field simulation

The numerical simulation of the cavitation water jet fluid field was performed using the ANSYS Fluent software, employing a two-dimensional axisymmetric model, as depicted in Fig. 4. The fluid field calculation involved simulation of gas-liquid two-phase mixed flow, hence the Mixture model in the multiphase flow category was selected. The RNG k- ϵ model was utilized for turbulence model, with corrections applied to the turbulence viscosity and strain rate. Owing to its high precision and convergence properties, the Zwart-Gerber-Belamri model was selected as the cavitation model.

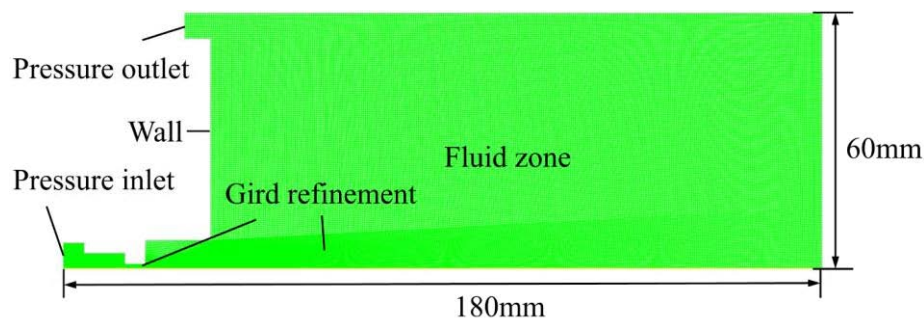


Fig. 4. Numerical model of cavitation water jet fluid field.

Figs. 5(a)-(c) display the pressure contours during the concentrated collapse of the cavitation

bubbles at different incident pressures. It is evident that the mechanical force of the cavitating water jet results from the high-energy shock waves produced by the concentrated collapse of cavitation bubbles. The impact pressures are 334 MPa, 426 MPa, and 501 MPa, respectively.

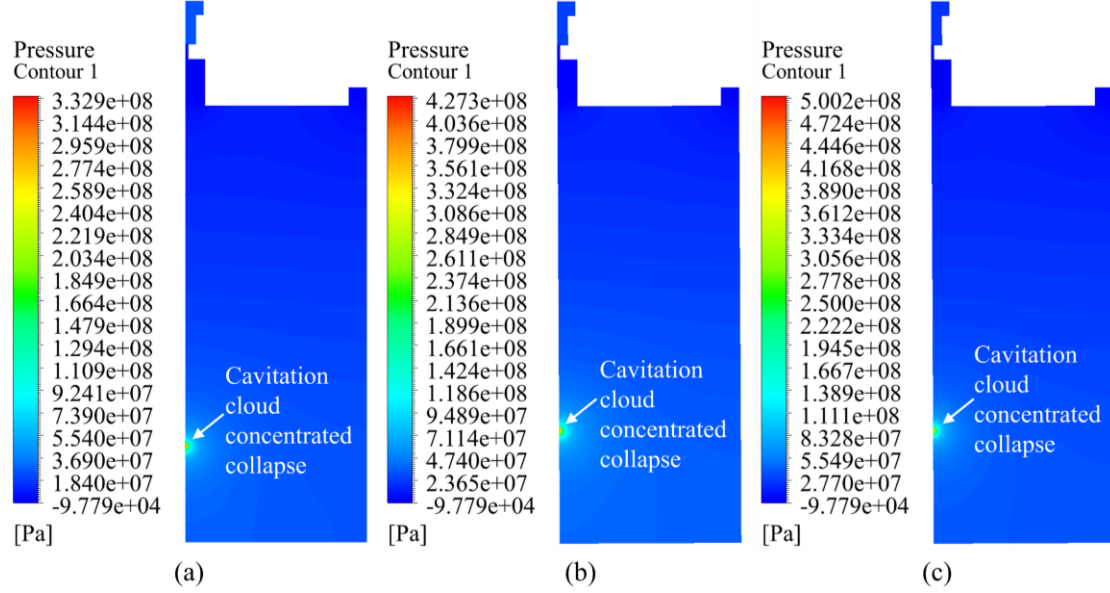


Fig. 5. The pressure contours of the concentrated collapse of cavitation bubbles under different incident pressures: (a) 15 MPa; (b) 20 MPa; (c) 25 MPa.

Subsequently, the Bernoulli equation was modified in accordance with the actual conditions, thereby transforming the pressure value of the cavitation water jet into the corresponding velocity parameter. The modified Bernoulli equation is expressed as follows [27]:

$$\frac{1}{2} \rho V^2 = \mu P_i (1 - \gamma P_0) \quad (1)$$

where γ and ρ are the compressibility coefficient and density of water ($\gamma = 5.1 \times 10^{-10} \text{ Pa}^{-1}$, $\rho = 1000 \text{ kg/m}^3$), V is the cavitation water jet velocity, P_i the impact pressure of cavitation water jet, P_0 is the incident pressure, the overflow coefficient of the nozzle μ is expressed as follows:

$$\mu = \partial_c (1 - 0.184 Re^{-0.2} I_0) \quad (2)$$

$$\partial_c = \left(\frac{d_0}{d_1} \right)^2 \quad (3)$$

in which ∂_c , Re , I_0 , d_1 , d_0 are the contraction coefficient of the nozzle, the Reynolds number in the nozzle, the length of the cylindrical section at the nozzle outlet with a diameter of d_0 , the diameter of the resonant cavity, the nozzle diameter, respectively. In this experiment, d_1 and I_0 are 5 mm and 3 mm, respectively. In summary, the cavitation water jet velocities corresponding to different

incident pressures are 213.97 m/s, 272.37 m/s, and 320.32 m/s, respectively.

3.2 RA-CWJP fluid-solid coupling simulation

The Coupled Eulerian-Lagrangian (CEL) algorithm was utilized to construct the fluid-solid coupling model for the RA-CWJP process, employing Abaqus/Explicit software, as shown in Fig.6. To simplify the calculations, a 1/4 model with a die hole diameter of 1.2 mm was established, and the blank holder and work base were excluded from the model. Given that the action area of the cavitating water jet is significantly larger than the die hole diameter [20], it is assumed that the cavitating water jet has a uniform size of 0.75 mm×0.2 mm and is evenly loaded onto the rubber surface. The contact surface is managed using penalty function coupling, with the liquid viscosity, gravity, surface tension, and thermal effects being neglected. The constitutive equation of water is represented by the Mie-Gruneisen state equation. The boundary conditions for the cavitation water jet, rubber, and workpiece are set to allow movement solely along the Z-axis direction. The cavitating water jet is modeled using the Eulerian grid, with the minimum sizes set to 0.01 mm. All solid components are meshed using the C3D8R element type, with the minimum mesh sizes of the rubber membrane, the mask, and the die set to 0.01 mm, 0.02 mm, and 0.02 mm, respectively. Additionally, the mesh size of the copper foil is set to 0.01 mm, and localized refinement is applied to the mesh near the die edge. The details of the grid refinement will be discussed in the following paragraphs.

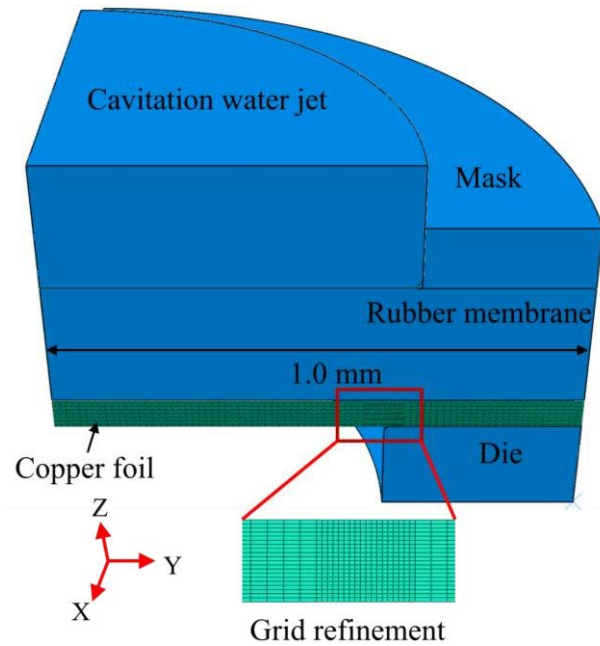


Fig. 6. The fluid-solid coupling model of RA-CWJP

The Johnson-Cook constitutive model is employed to simulate the dynamic deformation process of copper foil under high strain rate [28], while neglecting the effect of temperature. The model can be simplified as:

$$\sigma = (A + B\varepsilon_p^n)[1 + C \ln(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0})] \quad (4)$$

where A , B , n and C are the material parameters, ε_p is the equivalent plastic strain, $\dot{\varepsilon}$ and $\dot{\varepsilon}_0$ are the strain rate and reference strain rate under quasi-static loading, respectively.

The Johnson–Cook fracture criterion is used to predict the fracture of copper foil [29]. The model after ignoring the influence of temperature can be simplified as:

$$\varepsilon_f = \left[D_1 + D_2 \exp(-D_3 \sigma^*) \right] \left[1 + D_4 \ln(\varepsilon^*) \right] \quad (5)$$

where ε_f is the fracture strain, σ^* represents the dimensionless pressure-deviatoric stress ratio, D_1 - D_4 are failure constants. The relevant parameters of copper foil are shown in Table 2.

Table 2 Parameters in Johnson-cook constitutive model and failure criterion of copper foil [30]

Parameter	A (MPa)	B (MPa)	C	n	D_1	D_2	D_3	D_4
Value	89.63	291.64	0.025	0.31	0.3	0.28	-3.03	0.014

The Polyurethane rubber is considered as a hyperelastic incompressible material, and its deformation behavior is modeled using the Mooney-Rivlin model. The strain energy equation is given by [31]:

$$\sigma_{ij} = \frac{\partial W}{\partial \varepsilon_{ij}} \quad (6)$$

$$W = \sum_{k+m=1}^n C_{km} (I_1 - 3)^k + (I_2 - 3)^m + \frac{1}{2} k (I_3 - 1)^2 \quad (7)$$

where W represents the strain energy per unit volume, I_1 , I_2 and I_3 are invariants in the variable row tensor, and $I_3 = 1$ indicates that the material is incompressible. C_{10} and C_{01} represent the hyperelastic deformation behavior of rubber. The parameters of polyurethane rubber are shown in Table 3.

Table 3 Mechanical properties of polyurethane rubber [32]

Parameter	Hardness shore A (°)	M-R constant C_{10} (MPa)	M-R constant C_{01} (MPa)	Poisson's ratio (ν)
Value	70	0.382	0.096	0.4999

In the RA-CWJP process, the interaction between the copper foil and die edge is crucial,

requiring local grid refinement of copper foil near the die edge, as shown in Fig. 6. Fig.7 presents a comparison of the cross-sectional morphology of the micro-punched hole obtained from both the experimental and simulation results when the incident pressure is 20 MPa. The simulation result is generally consistent with the experimental result, which comprises three characteristic zones: rollover zone, shearing zone, and burr zone. To further optimize the numerical model and examine the effect of mesh size on the numerical simulation results, the percentage of shearing zone depth was compared with the experimental result (51.7%), and the relative error was calculated to assess the model's accuracy.

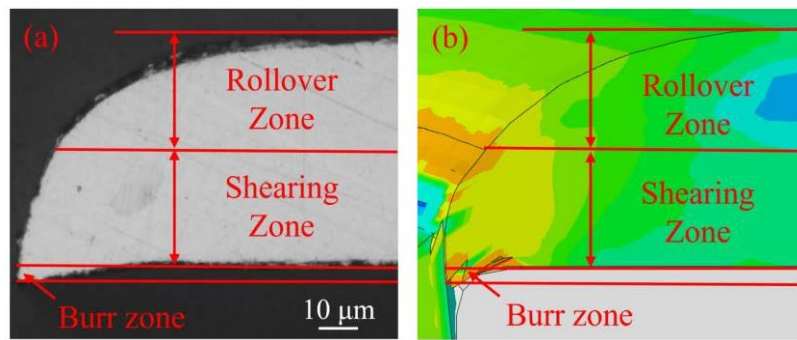


Fig. 7 Cross-section of micro-punched hole under the incident pressure 20 MPa: (a) experimental; (b) numerical simulation.

As shown in Table 4, as the mesh size decreases, the proportion of the shearing zone in the numerical simulation becomes closer to the experimental results, thereby reducing the relative error and improving simulation accuracy. However, a substantial reduction in mesh size leads to a significant increase in computational time. To strike a balance between accuracy and computational efficiency, a minimum mesh element characteristic length of 0.003 mm was chosen for the copper foil near the die edge. The relevant numerical simulation results are shown in Fig. 7(b).

Table 4 Effect of mesh size on numerical model accuracy

Minimum mesh element characteristic length (mm)	The percentage of shearing zone (%)	Relative error (%)
0.005	45.9	11.2
0.004	47.3	8.5
0.003	49.7	3.9
0.002	50.1	3.1
0.001	50.3	2.7

4. Results and discussion

4.1 Process window of incident pressure and rubber membrane thickness

Fig. 8 presents the experimental results of the copper foil subjected to the CWJP and RA-CWJP processes at an incident pressure of 15 MPa and a die hole diameter of 1.0 mm. Specifically, Fig. 8(a) and (b) depict the CWJP and RA-CWJP processes with a rubber membrane thickness of 200 μm , respectively, both of which successfully achieved micro-punching. In contrast, when the rubber membrane thickness is 100 μm or 300 μm , the copper foil undergoes only tensile deformation and incomplete fracture separation, as illustrated in Fig. 8 (c) and (d). Therefore, the thickness of the rubber membrane plays an important role in the micro-punching process, and its thickness needs to be selected reasonably.

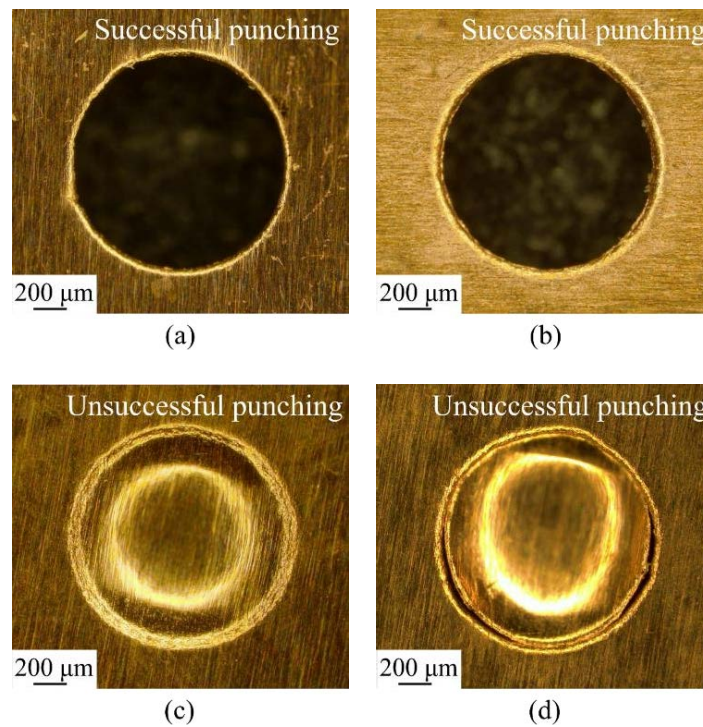
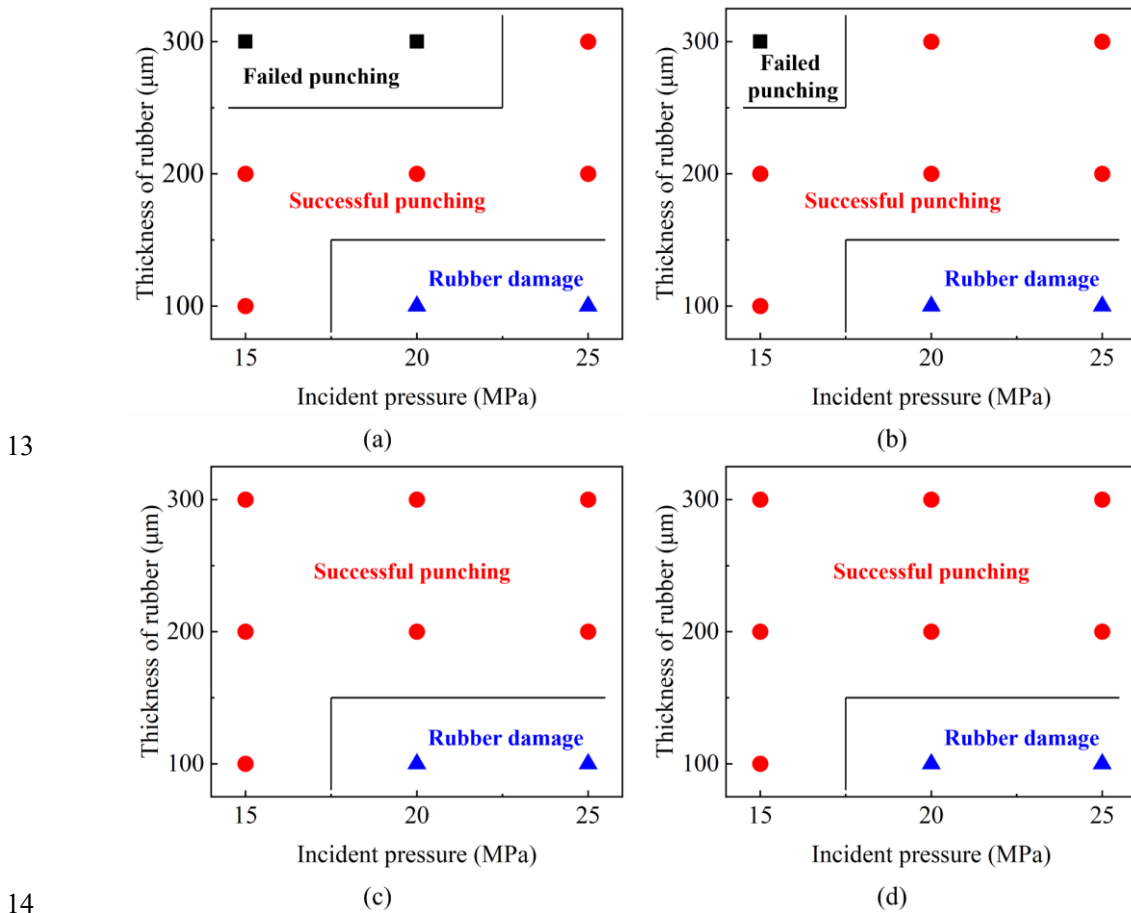


Fig. 8. Micro-punching results of two processes: (a) the CWJP process; (b)-(d) the RA-CWJP process with membrane rubber thickness of 200 μm ; 100 μm and 300 μm .

To further determine the optimal thickness of the rubber membrane, the process windows of the incident pressure and rubber membrane thickness is established under varying die hole diameters, as shown in Fig. 9. Observations from Figs. 9(a)–(d) indicate that when the rubber membrane thickness is 100 μm , complete punching of the workpiece can be achieved at an incident pressure of 15 MPa across all die hole diameters. However, when the incident pressure increases to 20 MPa and 25 MPa, the rubber membrane is breached by the cavitation impact pressure. This breach allows the high-speed cavitation water jet to form a “water cushion” between the rubber membrane and workpiece. The resultant reverse force from this “water cushion” hinders contact between the rubber

1 and workpiece, leading to micro-punching failure. When the rubber membrane thickness is 300 μm ,
2 micro-punched holes cannot be achieved at 15 MPa for die hole diameters of 1.0 mm and 1.2 mm,
3 as shown in Fig. 9(a). Similarly, micro-punching is not feasible at 20 MPa for a die hole diameter
4 of 1.0 mm, as depicted in Fig. 9(b). This is because as the aperture decreases, the geometric
5 constraint on the workpiece increases, raising the material's plastic deformation resistance and
6 requiring a higher punching force. Moreover, a thicker rubber membrane absorbs more of the
7 cavitation water jet impact force, reducing the punching force available for the copper foil. In
8 contrast, when the rubber membrane thickness is 200 μm , micro-punching can be successfully
9 achieved for all die hole diameters under various incident pressures. The results exhibit good
10 consistency with the die hole, and the rubber membrane remains undamaged, as shown in Fig. 8(c).
11 Consequently, a rubber membrane with a thickness of 200 μm was selected as the force transmission
12 medium for the RA-CWJP process.



13
14
15 Fig. 9. Process windows of incident pressure and rubber thickness under different die hole
16 diameters: (a) 1.0 mm; (b) 1.2 mm; (c) 1.4 mm; (d) 1.6 mm.

17 4.2 Effect of backflow and rubber membrane on fracture characteristics and fracture modes

Fig. 10 displays the fracture surfaces and cross-sections of the micro-punched holes formed by the CWJP process under different incident pressures, with a die hole diameter of 1.2 mm. When the incident pressure is 15 MPa, the fracture surface and cross-section can be divided into three characteristic zones: rollover zone, shearing zone, and burr zone, as shown in Fig. 10 (a) and (b). The rollover zone is formed due to the initial bending and tensile deformation of the material when the impact force acts on the copper foil and presses it into the die cavity. The shearing zone is formed due to the fracture separation caused by the intense shear action of the die hole edge. During the plastic shear fracture process, the material is subjected to tensile stress, resulting in an angle between the shearing zone and the vertical direction. Burrs are formed from the gradual expansion of micro-cracks at the die hole edge under tensile stress, typically located at the end edge of the micro-punched hole. Additionally, numerous plastic slip bands are distributed across the cross-section. This phenomenon occurs because when the impact force acts on the anisotropic polycrystalline copper foil, the material's plastic slip process is influenced by the mutual restraint between the grains, leading to multiple slip systems. These slip systems intersect and ultimately form plastic slip bands [33]. Therefore, under this incident pressure, the fracture mode of the micro-punched hole is a ductile fracture.

As the incident pressure increases to 20 MPa, an irregular distribution of the fracture surface is observed, as shown in Fig. 10(c). Region I displays a fracture morphology similar to that at 15 MPa, where ductile fracture still prevails. In contrast, region II exhibits distinct fracture characteristics, with reduced plastic deformation and obvious backflow reverse impact traces. Brittle fracture characteristics, such as river patterns, are evident, indicating that this region experiences brittle fracture. Fig. 10(d) illustrates the cross-sectional morphology of region II, which only has a narrow rollover zone. The cross-sectional profile is nearly perpendicular to the punching direction, and sharp protrusion-like structures appear due to the reverse impact of backflow, further confirming the characteristics of brittle fracture. At 25 MPa, compared with 20 MPa, the entire fracture surface is relatively flat with significant warping deformation, as shown in Fig. 10(e). In the magnified local view, numerous river patterns are present, indicating that the fracture mode is brittle fracture. The cross-sectional morphology reveals that the proportion of the rollover zone is minimal, the material does not exhibit obvious plastic deformation characteristics, and the cross-sectional profile is relatively flat and sharp. This morphology suggests that the material undergoes little plastic flow

during the micro-punching process, instead rapidly fractures under high stress concentration, exhibiting a typical brittle fracture mode, as shown in Fig. 10(f).

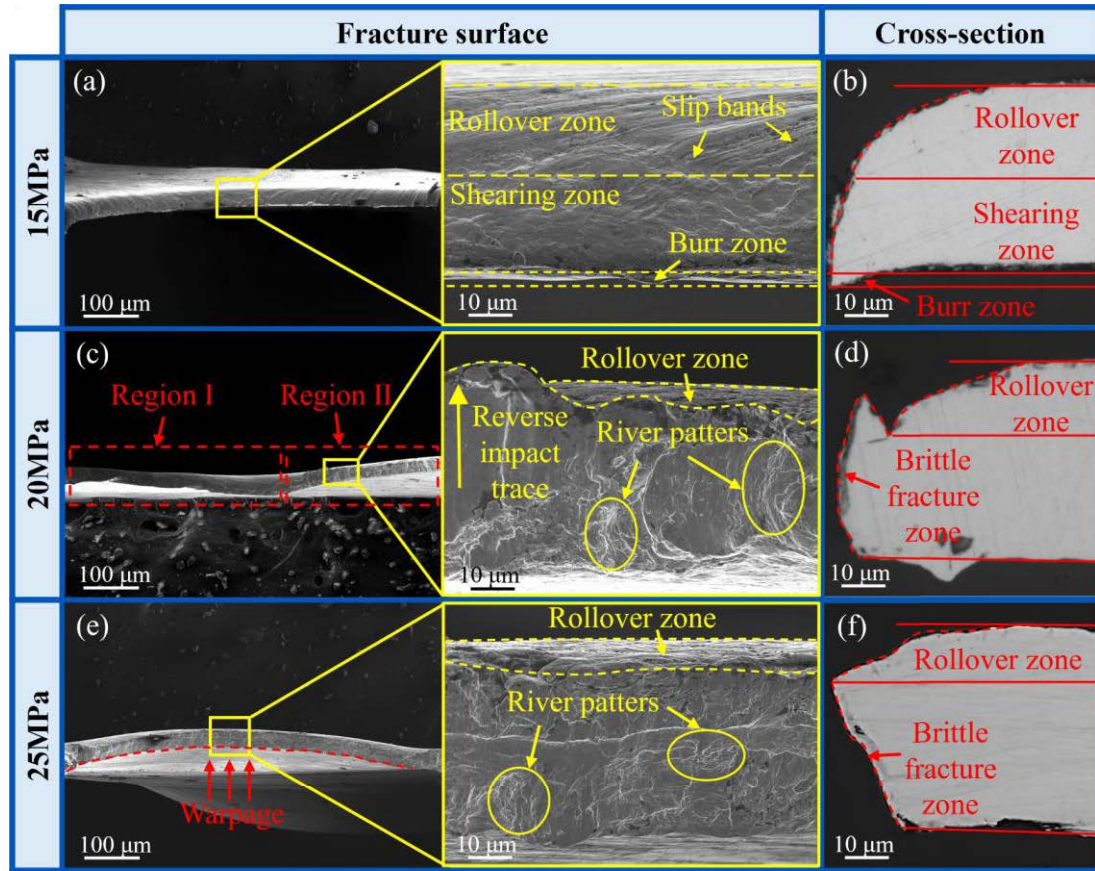


Fig. 10. The fracture surface and cross-section of micro-punched holes formed by the CWJP process under different incident pressures. (a) and (b) 15MPa; (c) and (d) 20MPa; (e) and (f) 25MPa.

Given that the backflow of the cavitating water jet generates a reverse impact force within the die hole during direct punching, which leads to the irregular fracture surface distribution and brittle fracture of the micro-punched holes, the schematic diagram of the CWJP process is presented in Fig. 11. When the cavitation water jet directly impacts the copper foil, it undergoes plastic tensile deformation, as shown in Fig. 11(a). As the impact force reaches the tensile strength of the copper foil, micro-cracks begin to form on the lower surface at the die hole edge, as depicted in Fig. 11(b). Due to slight differences in the force experienced by the workpiece at the die edge and local variations in its mechanical properties, the distribution of micro-cracks is not uniform [34]. As illustrated in Fig. 11(c), with the sustained action of the impact force, the micro-cracks rapidly propagate towards the upper surface, resulting in initial localized fracture at the die edge. At this stage, the cavitating water jet enters the die cavity through the local fracture and impacts the bottom

of the die hole, causing high-speed backflow reverse impacts on the copper foil at the die hole edge. Additionally, the water retained in the die cavity forms a “water cushion” effect, further diminishing the impact force. Furthermore, the unbroken copper foil at the die hole edge is fractured and separated under the combined action of the cavitation water jet impact and backflow reverse impact until the punching process is completed, as shown in Fig. 11(d).

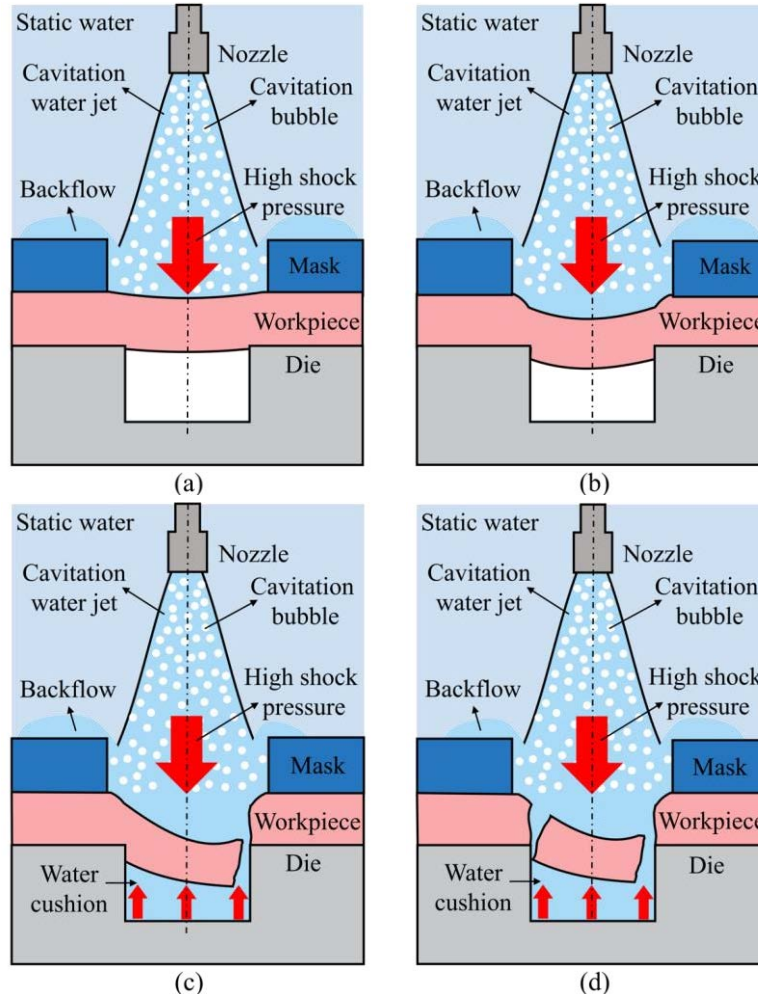


Fig. 11. Diagram of the entire CWJP process: (a) bulging deformation stage; (b) micro-crack formation stage; (c) local fracture stage; (d) punching completed.

Moreover, the backflow reverse force and the “water cushion” stranded in the die cavity alter the stress state of the workpiece at the die edge. Fig. 12 presents the mechanical schematic of the workpiece during the CWJP process. In addition to the cavitation water jet impact pressure, the clamping force of the mask and die, and the lateral pressure of the die edge, the material in the deformation zone is also subjected to the reverse force from backflow and the “water cushion”. When the incident pressure is 15 MPa, the reverse force is lower than the impact force. The copper foil in the fracture zone is subjected to the axial tensile stress σ_r and the radial tensile stress σ_t due

to the combination effects of die hole edge and impact force, leading to ductile fracture, as shown in Fig. 12(a). However, as incident pressure increases 20 MPa or 25 MPa, reverse force exceeds the impact force, and the copper foil is no longer subjected to the lateral pressure of the die corner. It instead experiences unidirectional tensile stress σ_1 in the axial direction, caused by the impact of cavitation water jet and backflow, resulting in brittle fracture of workpiece, as shown in Fig. 12(b).

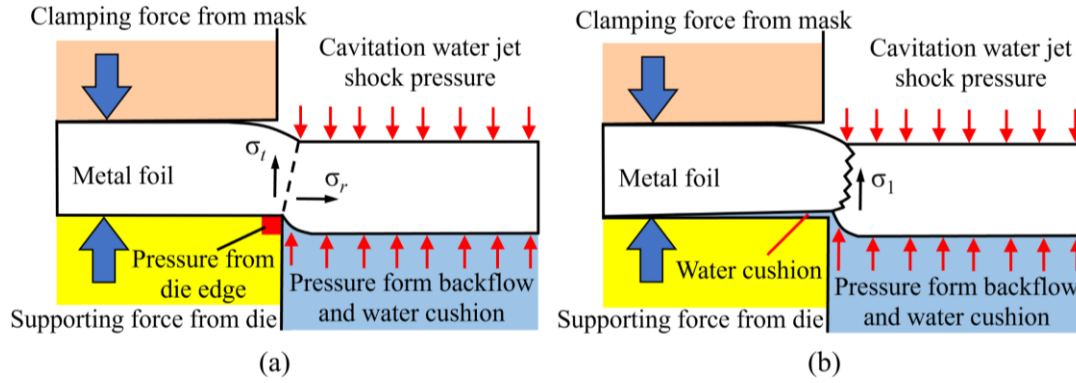


Fig. 12. Mechanical schematic of copper foil under different incident pressures with the CWJP process.

Figs. 13(a)–(c) show the fracture surfaces and cross-sections of micro-punched holes formed by the RA-CWJP process under different incident pressures, with a die hole diameter of 1.2 mm. It can be observed that the fracture surfaces and cross-sections consist of the rollover zone, the shearing zone, and the burr zone, indicating ductile fracture modes. In comparison with Fig. 10, it is evident that at 15 MPa, the micro-punched holes exhibit similar fracture characteristics in both processes, the fracture mode is unchanged. At 20 and 25 MPa, no irregular distribution or brittle failure is observed in the fracture surfaces and cross-sections under the RA-CWJP process. The forming quality of micro-punched holes is significantly improved with the aid of rubber membrane.

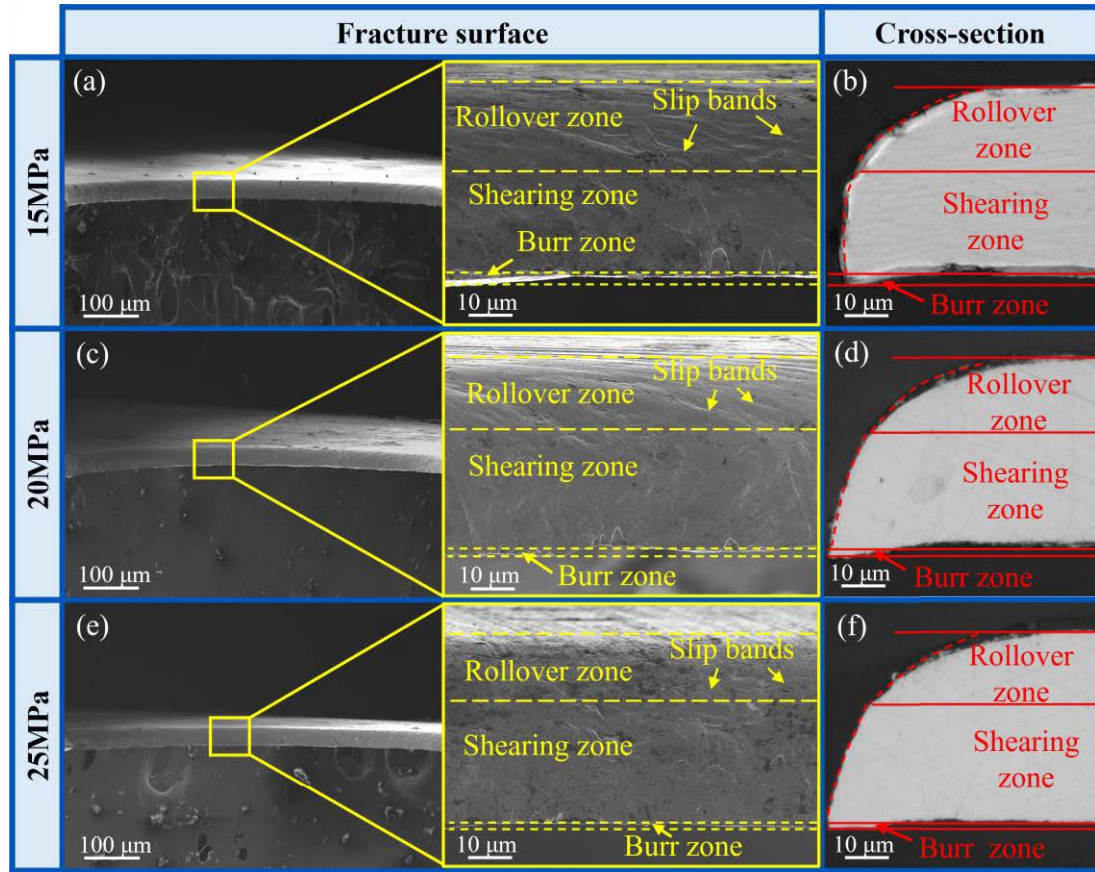


Fig. 13. The fracture surface and cross-section of micro-punched holes formed by the RA-CWJP process under different incident pressures: (a) and (b) 15MPa; (c) and (d) 20MPa; (e) and (f) 25MP.

To further examine the influence of the rubber membrane on fracture surface morphology, the depth percentages of different zones of micro-punched holes formed by two processes are illustrated in Fig. 14. All experiments were conducted at an incident pressure of 15 MPa, where the effect of the backflow was minimal. This study employs an analytical methodology for assessing the depth percentages of different zones on the cross-section, as utilized in other micro-punching processes [35]. The depth percentage of each zone was determined by measuring the depth of the individual zones and dividing it by the total cross-sectional length, thereby deriving the respective depth percentages. The experimental results show that the RA-CWJP process achieves a maximum reduction of 14.2% and 1.3% in the depth percentages of the rollover and burr zones, respectively, and a maximum increase of 15.6% in the shearing zone, compared to the CWJP process. These findings indicate a substantial enhancement in the quality of the fracture surface, which is attributable to the influence of the rubber membrane.

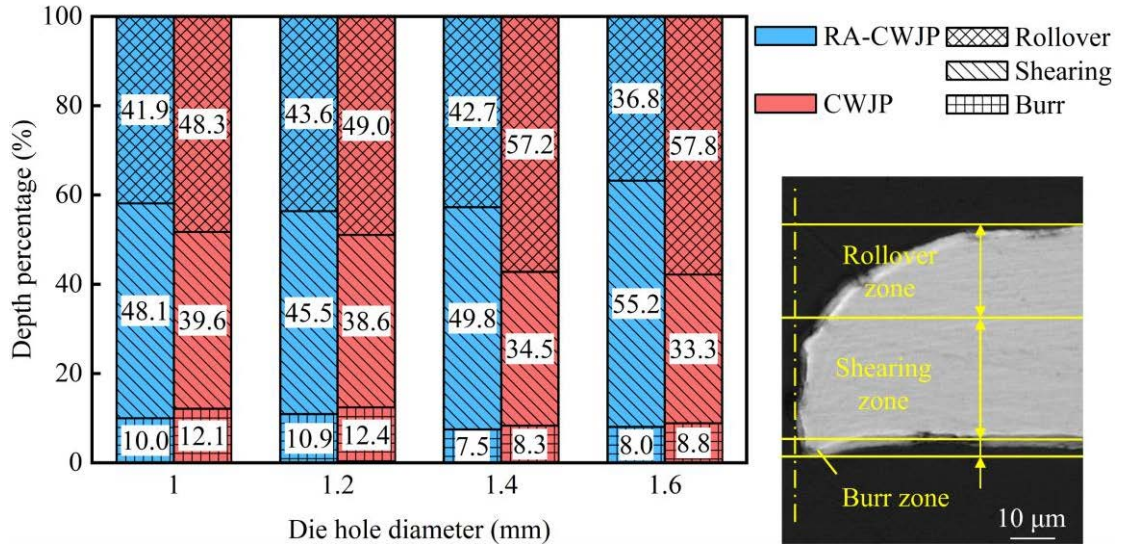


Fig. 14. Influence of rubber membrane on dimensions of different zones of micro-punched holes.

Fig. 15 depicts the dynamic deformation and fracture process of the copper foil during the RA-CWJP process at an incident pressure of 20 MPa, as obtained through numerical simulation. Upon the application of the cavitating water jet impact force to the surface of the rubber membrane, the rubber initially undergoes compression and deformation, thereby forming a flexible punch aligned with the direction of the die cavity. As the impact force persists, the copper foil positioned above the die hole is subsequently squeezed by the rubber, resulting in deformation that follows the rubber's movement. At this stage, the copper foil is subjected to shear force at the edge of the die hole and compression force from the rubber, leading to stress concentration within the copper foil at this location. Over time, the sustained impact force further enhances plastic deformation, and the internal stress in the copper foil at the edge gradually approaches its tensile strength. Cracks initiate on the lower surface of the copper foil, marking the onset of shear separation. These cracks propagate in areas of stress concentration, eventually coalescing and resulting in complete fracture separation. Notably, in the RA-CWJP process, the rubber membrane functions as a soft punch, thereby preventing direct contact between the cavitating water jet and the workpiece surface. This effectively mitigates the backflow reverse impact and the formation of a water cushion, thereby avoiding irregular distribution and brittle fracture of the fracture surface. Furthermore, the incorporation of rubber into the process increases the proportion of compressive stress experienced by the copper foil during shear separation, thereby reducing the proportion of tensile stress, which delays the generation of cracks. Thus, the duration of plastic shear at the die hole edge is extended,

leading to an increase in the shearing zone and an improvement in the fracture surface quality.

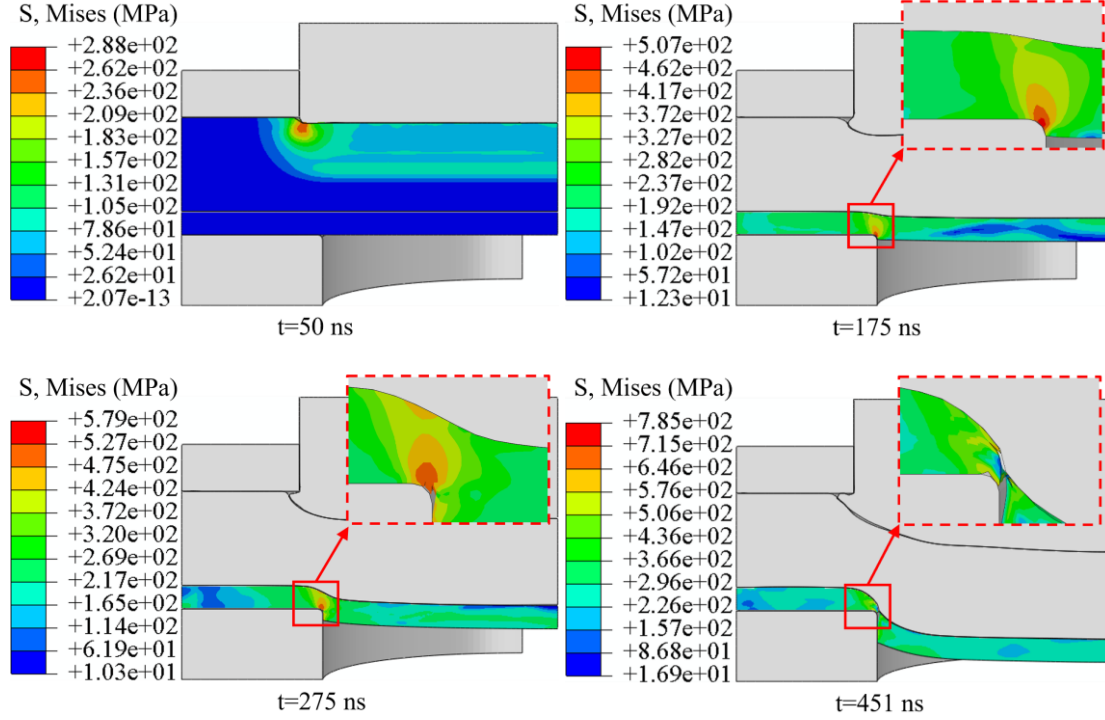


Fig. 15. Dynamic deformation and fracture process of copper foil in the RA-CWJP process.

4.3 Effect of rubber membrane on shape accuracy

Fig. 16 illustrates the macroscopic morphology of the micro-punched holes formed by the CWJP and RA-CWJP processes under varying incident pressures, with a die hole diameter of 1.6 mm. The micro-punched holes formed by the CWJP process exhibit defects, such as warpage deformation and edge tearing, which exacerbate with increasing incident pressure, as evidenced in Fig. 16(a). As depicted in Fig. 12, the reverse impact of the backflow subjects the micro-punched holes to a bending moment, causing warping deformation. Additionally, the workpieces are subjected to bidirectional forces from the impact and backflow, leading to severe uneven forces that tear the micro-punched holes, resulting in an irregular contour. In contrast, the RA-CWJP process produces micro-punched holes with a surface free of warpage or tearing, maintaining a well-defined circular profile, as shown in Fig. 16(b).

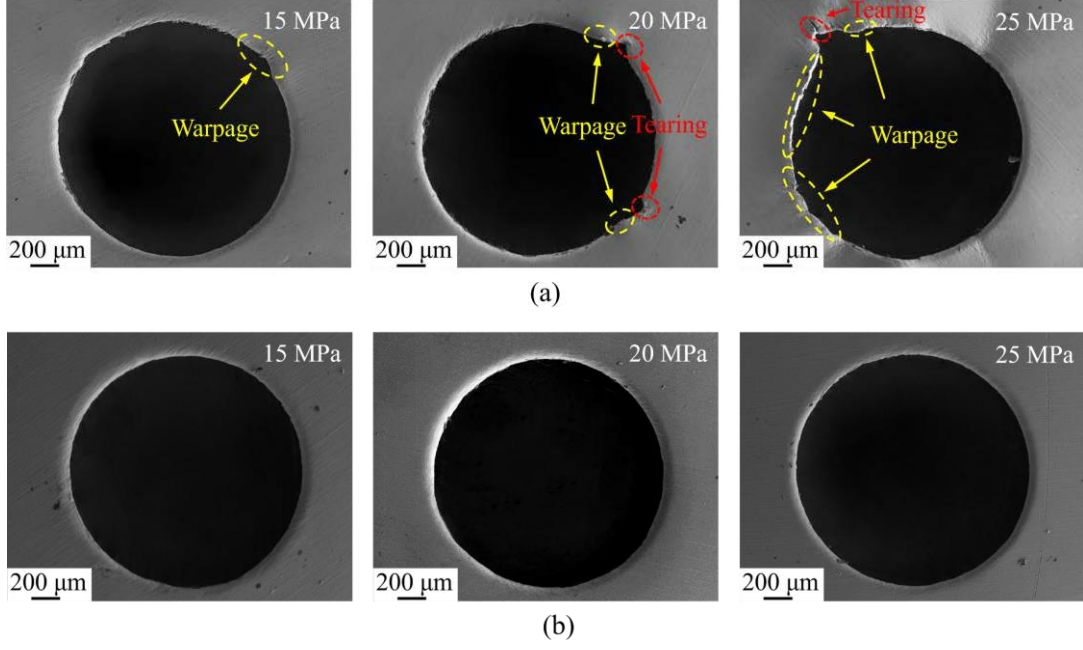


Fig. 16. The macroscopic morphology of micro-punching holes formed by two micro-punching processes: (a) CWJP process; (b) RA-CWJP process.

To further assess the effect of the rubber membrane on the shape accuracy of the micro-punched holes, roundness is used as a quantitative measure of shape accuracy. The roundness is defined as [36]:

$$\text{Roundness} = R_{\max} - R_{\min} \quad (8)$$

where $R_{\max}$ and $R_{\min}$ represent the radii of the circumscribed and inscribed circles of the micro-punched holes, respectively. The methodology for measuring roundness is illustrated in Fig. 17. Five samples were evaluated for each condition, and the means and standard deviations were computed. A smaller roundness value signifies a closer approximation of the holes to a theoretical circle, indicating higher shape accuracy.

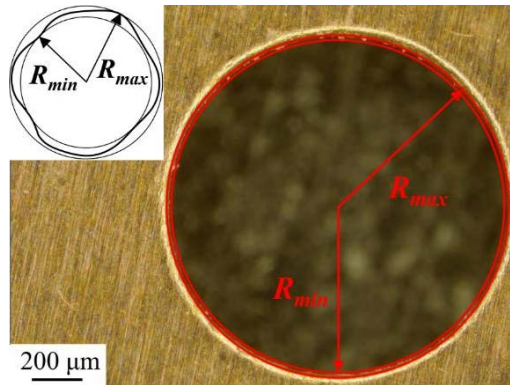


Fig. 17. The roundness measurement method of micro-punched holes.

The roundness measurement results of the micro-punched holes formed by the RA-CWJP and CWJP processes are shown in Fig. 18. Fig. 18(a) compares the roundness of the micro-punched holes produced by these two processes under varying incident pressures, with a die hole diameter of 1.4 mm. As the incident pressure rises from 15 MPa to 25 MPa, the roundness of holes punched formed by the CWJP process increases from 59.5 μm to 77.9 μm , suggesting a substantial deterioration in shape accuracy due to the backflow reverse force. However, as the incident pressure increases, the roundness of holes formed by the RA-CWJP process decreases from 35.9 μm to 28.4 μm , corresponding to improvements in shape accuracy of 39.6%, 50.1%, and 63.5%, respectively. Fig. 18(b) compares the roundness of micro-punched holes formed by the two processes across different die hole diameters, with all experiments conducted at an incident pressure of 15 MPa to minimise the effects of backflow. It is evident that the RA-CWJP process yields higher shape accuracy compared to the CWJP process. Specifically, when the die hole diameter is 1.0 mm, the roundness values for the CWJP and RA-CWJP processes are 53.8 μm and 45.1 μm , respectively, representing an 8.7 μm difference and a 16.1% enhancement in shape accuracy. For die hole diameters ranging from 1.2 mm to 1.6 mm, the roundness differences between the two processes increase substantially to 20.6 μm , 19.6 μm , and 20.9 μm , respectively, resulting in shape accuracy improvements of 39.1%, 35.3%, and 37.7%, respectively.

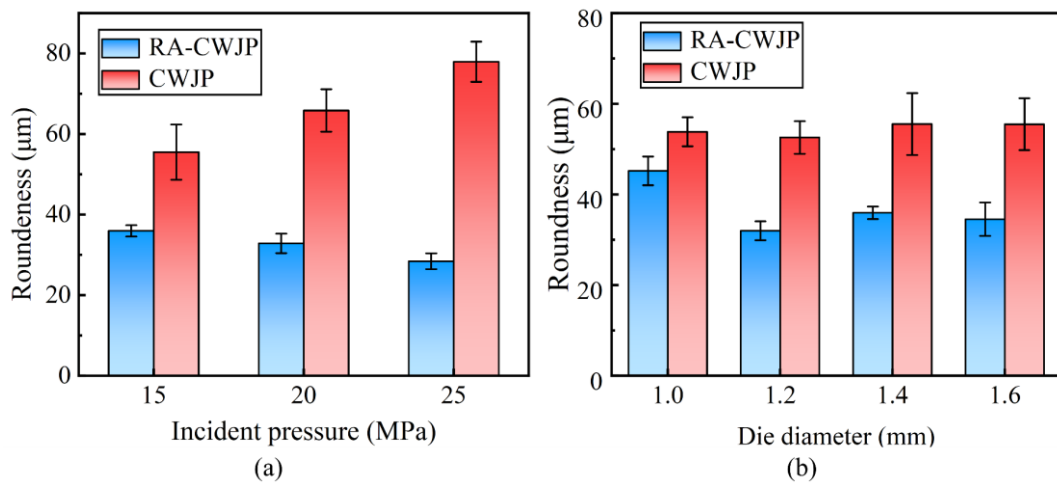
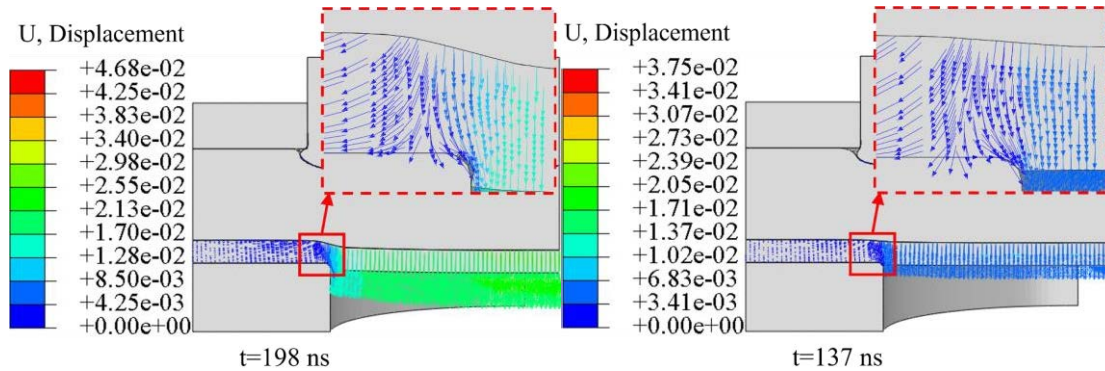


Fig. 18. The roundness comparison of micro-punched holes formed by the RA-CWJP and CWJP processes. (a) The roundness comparison under diffident incident pressures, (b) The roundness comparison under varying die hole diameters.

The experimental results presented above demonstrate that the introduction of a rubber membrane improves the shape accuracy of micro-punched holes. This improvement is achieved not

only by protecting the workpiece from the effect of backflow, but also by leveraging the superior fluidity of the rubber membrane. This fluidity optimizes the flow behavior of the copper foil at the die hole edge, particularly during the crack propagation stage. To further investigate this phenomenon, a numerical simulation of the RA-CWJP process was conducted at an incident pressure of 25 MPa, with the material flow behavior at the die hole edge observed, as shown in Fig. 19. Upon the application of the cavitating water jet to the rubber membrane, its incompressible and highly elastic properties enable the formation of a soft punch with liquid-like fluidity above the die cavity. The soft punch undergoes both axial and radial deformation, effectively transmitting the transient impact force. At 137 ns, the copper foil begins to exhibit flow behavior along the die hole cavity. As the pressure continues to increase to 198 ns, the copper foil enters the crack propagation stage. During this phase, when subjected to axial and radial pressures from the rubber membrane, the copper foil conforms to the surface of the die hole and exhibits flow behavior along its edge. Complete shearing separation of the copper foil at the die hole edge occurs when the load reaches 401 ns. In evidence, during the crack propagation stage, the copper foil, compressed by the rubber membrane, is tightly sheared against the die hole edge, resulting in a smoother edge for the micro-punched holes and a contour shape that more closely resembles the die hole. This significantly improves the shape accuracy of the micro-punched holes. However, when the die hole diameter is excessively small (e.g., 1.0 mm), the rubber membrane cannot fully fill the die hole cavity, which prevents the rubber and workpiece from deforming in unison. Consequently, the improvement in shape accuracy afforded by the rubber membrane is reduced.



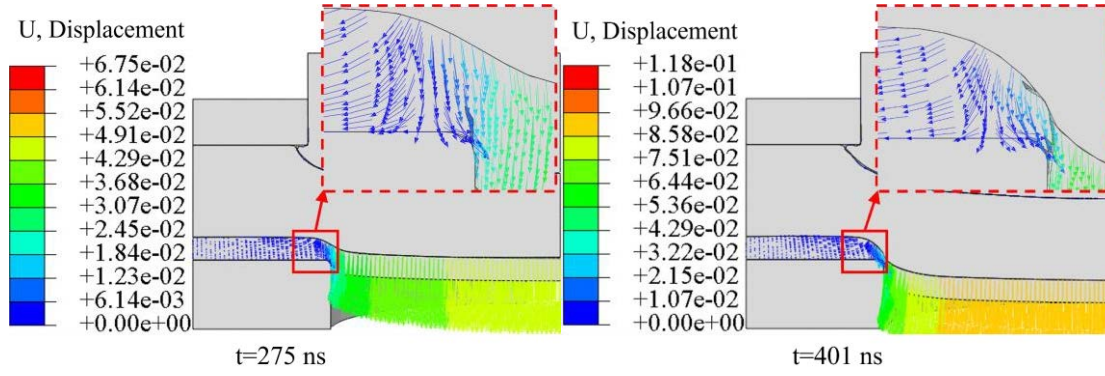


Fig. 19. The flow behavior of copper foil at the die hole edge under the RA-CWJP process.

4.4 Effect of rubber membrane on dimensional accuracy

To further investigate the effect of the rubber membrane on the machining accuracy of the micro-punched holes, the dimensional deviation (D_v) is used as a quantitative measure of dimensional accuracy. The calculation formula is as follows [37].

$$D_v = D_p - D_d \quad (9)$$

where D_p , D_d represent the diameters of the micro-punched hole and die hole, respectively. The micro-punched hole diameter is defined as the outlet diameter, and its measurement method is depicted in Fig. 20. The mean value of D_v was measured five times along the circumferential equidistant positions, and this procedure was repeated under each condition to obtain both the mean and standard deviation of D_v . A smaller D_v value indicates a smaller deviation between D_p and D_d , leading to higher dimensional accuracy.

Fig. 20 illustrates the dimensional deviation of the micro-punched holes formed by the RA-CWJP and CWJP processes across various incident pressures and die hole diameters. It is observed that the diameters of micro-punched holes in both processes consistently exceed those of the corresponding die holes. According to the previous analysis, the workpiece is subject to tensile and bending deformation during the micro-punching process. Upon unloading after processing, the elastic recovery occurs, leading to a dimensional deviation between the micro-punched hole and die hole [38].

Furthermore, Fig. 20(a) presents a comparative analysis of the dimensional accuracy of the micro-punched holes formed by the two processes under varying incident pressures, with a constant die hole diameter of 1.4 mm. As the incident pressure increases, the D_v values in the CWJP process increase from 48.9 μm to 81.5 μm , indicating a deterioration in dimensional accuracy with higher

incident pressure. In contrast, the RA-CWJP process exhibits a reduction in dimensional deviation, with the D_v values ranging from 14.5 μm to 23.4 μm . The reduction in the D_v values varies from 56.0% to 82.2%. Fig. 20(b) shows the comparative analysis of the dimensional deviation for the micro-punched holes formed by the two processes across different die hole diameters, at a constant incident pressure of 15 MPa. For the CWJP process, the D_v values range from 55.5 μm to 61.5 μm , while for the RA-CWJP process, these values span from 18.8 μm to 26.7 μm . The differences in D_v values between the two processes are 36.0 μm , 37.6 μm , 28.8 μm , and 40.7 μm , respectively, corresponding to a reduction in dimensional deviation ranging from 45.4% to 68.4%.

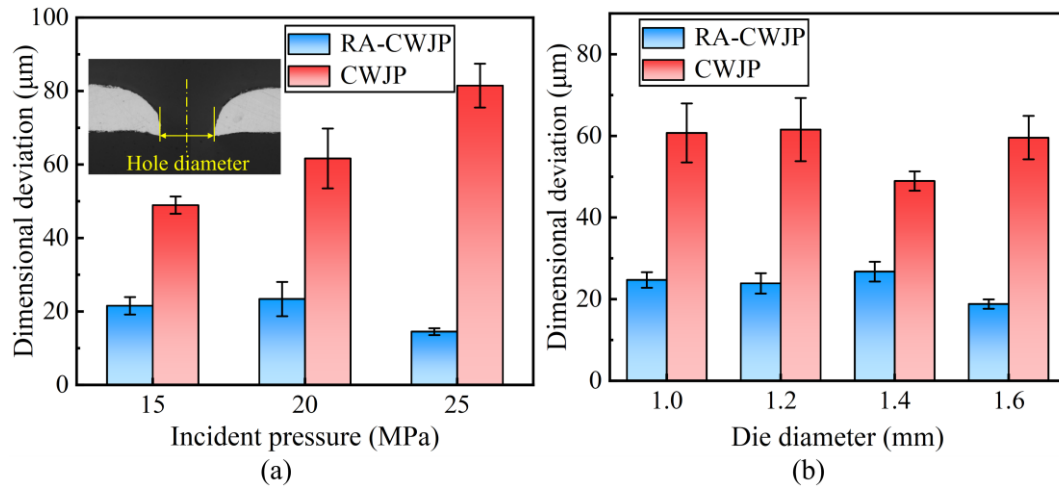


Fig. 20. Experimental results of dimensional accuracy of micro-punched holes formed by the RA-CWJP and CWJP processes under different conditions. (a) The comparison of dimensional accuracy under different incident pressures; (b) The comparison of dimensional accuracy under varying die hole diameters.

The experimental results mentioned above demonstrate the feasibility of improving the dimensional accuracy of micro-punched holes using a rubber membrane. Due to the rubber membrane's strong compressibility, it optimizes the stress state of the workpiece at the die hole edge, increasing the degree of plastic deformation during the micro-punching process. To this end, three positions are selected at equal intervals along the thickness direction of the workpiece at the die hole edge for three-dimensional stress analysis, and the variation of stress with time is shown in Fig. 21. The axial, radial, and circumferential stresses are denoted as σ_t , σ_r , and σ_θ , respectively. Given that the upper surface of the workpiece at position 1 is consistently in contact with the rubber membrane, the material remains in a three-dimensional compression state during the micro-punching process, as illustrated in Fig. 21(b). The workpiece at point 2 is located at the center of the deformation area.

1 During the plastic deformation stage, it experiences three-dimensional compressive stress due to the
2 pressure from the rubber membrane. As the impact duration increases, the workpiece flows toward
3 the die cavity, initiating the formation of micro-cracks. The three-dimensional compressive stress
4 transitions into axial and circumferential tensile stress and radial compressive stress. After complete
5 fracture, it exhibits a three-dimensional compressive stress state under the compression of the rubber
6 membrane, as shown in Fig. 21(c). Distinct from position 2, the workpiece at position 3 is subjected
7 to a three-dimensional tensile stress state during crack propagation due to its interface with the die
8 edge. Following the completion of fracture, it enters a state of three-dimensional compression stress
9 under the influence of the rubber membrane, as illustrated in Fig. 21(d). Consequently, under the
10 strong compressive force of the rubber membrane, the copper foil is primarily subjected to a three-
11 dimensional compressive stress state throughout the micro-punching process. This condition
12 improves the plasticity of the material, increasing the proportion of plastic deformation relative to
13 total deformation while diminishing elastic deformation. As a result, the amount of elastic recovery
14 deformation after unloading is reduced, thereby significantly enhancing the dimensional accuracy
15 of the micro-punched holes using the rubber membrane.

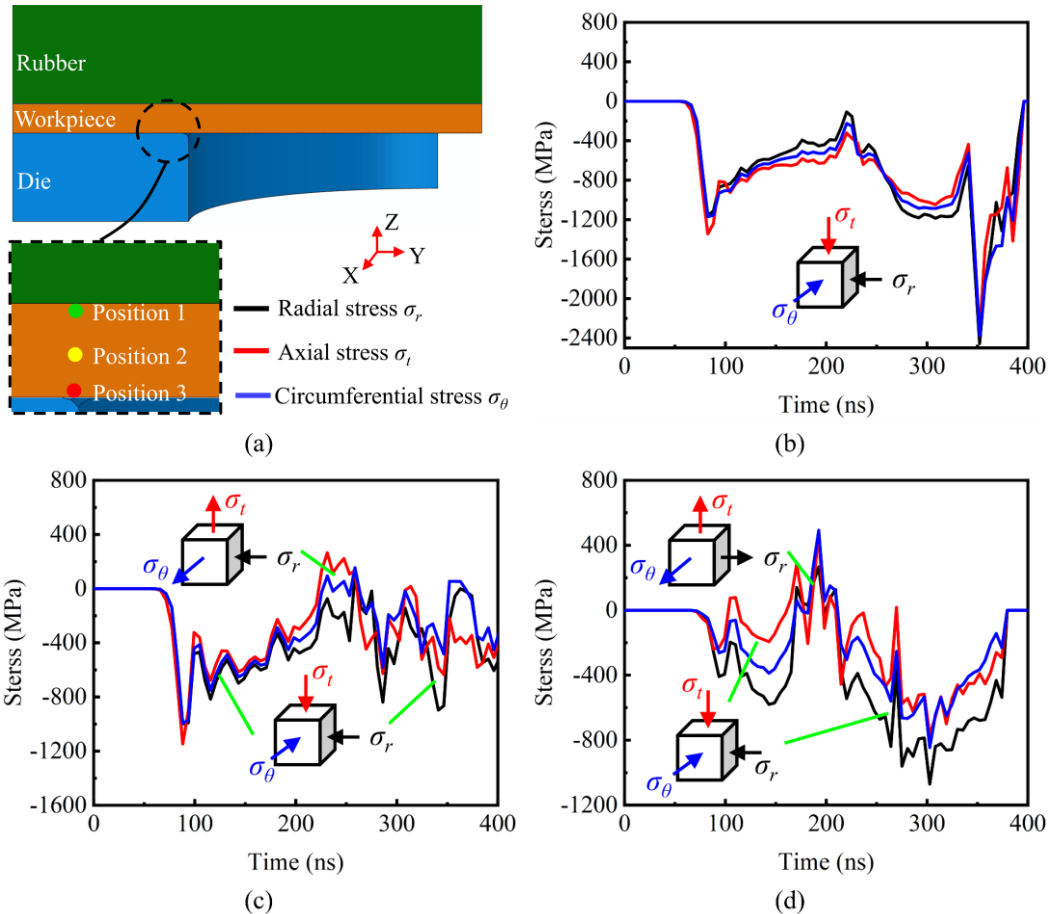


Fig. 21. The stress state of copper foil at the die hole edge in the RA-CWJP process: (a) location of position 1, 2 and 3; (b)-(d) stress histories of positions 1, 2 and 3.

5. Conclusion

In this study, a novel micro-punching method is proposed, utilizing the transient impact force of the cavitation water jet as the loading source and the rubber membrane as the force transmission medium. A series of comparative experiments were conducted using the RA-CWJP and CWJP processes. The process windows of incident pressure and rubber membrane thickness were established. The forming quality of micro-punched holes under the two processes was compared and analyzed from various perspectives, including fracture surface morphology, cross-sectional fracture morphology, shape and dimensional accuracy. Furthermore, the influence of high-speed backflow reverse impact on the CWJP process was investigated. Meanwhile, the improvement mechanism of the rubber membrane on the forming quality of micro-punched holes was revealed through the numerical simulation. The following conclusions can be drawn:

(1) The thickness of the rubber membrane significantly affects the RA-CWJP process. At a thickness of 100 μm , the soft punch is susceptible to damage under a high incident pressure, leading to the failure of micro-punching. Conversely, at a thickness of 300 μm , the elastic deformation of the rubber membrane consumes a substantial portion of the impact force, preventing the complete fracture separation of the copper foil. Consequently, under the given experimental conditions, the rubber membrane thickness of 200 μm is identified as the most suitable.

(2) The introduction of the rubber membrane can prevent the brittle fracture, warpage deformation, and edge tearing of micro-punched holes caused by the reverse impact force of high-speed backflow. Additionally, compared to the CWJP process, the RA-CWJP process achieves a maximum reduction of 14.2% and 1.3% in the depth percentages of the rollover and burr zones, respectively, and a maximum increase of 15.6% in the shearing zone.

(3) The rubber membrane significantly impacts the shape accuracy of the micro-punched holes, with improvements ranging from 19.3% to 63.5%. This is due to the effective mitigation of warping deformation and edge tearing, commonly caused by high-speed backflow reverse impact. Moreover, by utilizing the super-elasticity and incompressibility of the rubber membrane, the copper foil is tightly sheared against the die hole edge, resulting in micro-punched holes whose contour shapes closely approximate the die hole.

(4) The dimensional accuracy of micro-punched holes can be improved by 45.2% to 82.2% with the aid of rubber membrane. The significant compressive force generated by the rubber membrane induces a predominantly three-dimensional compressive stress state in the copper foil during the micro-punching process. This stress state facilitates an increased degree of plastic deformation, increasing the proportion of the plastic deformation within the total deformation. As a result, the elastic recovery deformation upon unloading is reduced.

Acknowledgements

The authors are grateful for the financial support from the Six Talent Peak Selection and Training Program of Jiangsu [XNYQC-002], the Natural Science Foundations of Jiangsu Province [BK20170752]. We would also like to express our gratitude to editors and anonymous reviewers for their helpful suggestions on the quality improvement of this article.

Declarations

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company in the manuscript entitled.

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2025-05-01

Springer

<https://doi.org/10.1007/s43452-025-01174-x>

Li F, Meng W, Mori S, et al., (2025) Investigation on the mechanism of improving the forming quality of cavitation water jet micro-punching by using a rubber membrane. Archives of Civil and Mechanical Engineering, Volume 25, Issue 3, May 2025, Article number 115