Numerical study of microplastic impact hydroforming process

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Abstract. Microplastic forming is a promising micro production technology with great advantages due to its excellent mechanical property, definite thermal stability and low manufacture cost. Impact hydroforming technology is a high strain rate forming method that can improve the limit of metal microplastic forming. In this study, FE-simulation is carried out to reveal the influence of different process parameters on the forming behaviors of micro impact hydroforming process. The forming depth is improved with the increase of the velocity. In addition, different areas of the formed parts are affected by the liquid pressure, bottom fillet, blank holder and friction condition. The strain distribution is inhomogeneous, and the ball head portion has the largest strain. The simulation result also shows the thinning effect is greatest at the center point and decreases from the center to the radius. Through the analysis of the process feasibility, the simulation results of microplastic impact hydroforming can provide references to the design and manufacture of actual impact hydroforming parts.

1. Introduction
With the rapid development of MEMS technology, especially in the field of electronic equipment, fuel cell and other industries, the demand for miniaturized products is increasing, and the manufacturing industry is facing new challenges. As one of the promising manufacturing processes for manufacturing micro parts, micro plastic forming is a kind of micro production technology attracting the attention of many researchers. Micro plastic forming technology has become a feasible, controllable and repeatable micro manufacturing technology in recent years and has been widely used in industrial manufacturing. Due to the size effect, the traditional scale deformation behavior is not suitable for predicting the material deformation behavior in the process of micro scale deformation [1]. Because of the lack of the understanding on size effect of micro scale forming, the size effect produced in the forming process could lead to the uncertainty on the process such as in the design of tools, and the product quality is difficult to control. Impact hydroforming belongs to high strain rate forming, which improve the limit of metal micro plastic forming. Also, it does not require centering, which overcomes the defects of general forming technology and can be widely implemented in large-scale production.

In the surface model proposed by Engel et al. [2], the samples are divided into surface layer and internal layer. The particles in the surface layer are less restricted than those in the interior, so they have less hardening and lower overall flow stress. This model has been improved by Geißdörfer et al. [3]. The material is subdivided into individual particles with individual characteristics whose size and position in the material affect its size effect. Lai et al. [4] established a constitutive material model for the change of flow stress with the specimen and grain sizes based on the surface layer model and Hall–Petch relation. Another improved method proposed by Raabe D et al. [5] assumes that the grains in the surface layer can be treated as single crystals, while the inner grains are regarded as part of polycrystalline aggregates, which is known as the improved Hall-Petch relation. In general, plastic
deformation is mainly caused by dislocation slip. Some researchers modified the traditional crystal plastic model to further explain the relationship between the evolution of dislocation slip and size effect. Raabe et al. [6] used finite element simulations to study the influence of the stability of the initial crystal orientation, sample geometry and friction on the anisotropy and crystallographic orientation changes during such tests. Tensile test was conducted with annealed pure copper foils with different thicknesses and grain sizes to study the size effects on fracture behaviors. In Chan et al. [7], flow stress, fracture stress and strain, and the number of micro-voids on the fracture surface decrease with the decreasing ratio of specimen size to grain size. Meanwhile, the realization of micro plastic forming is also limited by the forming die. The punch and die of micro plastic forming to further improve the feasibility of micro plastic forming are studied as well. Fu et al. [8] designed and fabricated different size-scaled compound micro blanking and deep drawing dies. The influence of punch radius on the deformation load is shown in Fig. 1. It can be seen that the deformation load decreases with the increase of punch radius.

Impact hydroforming (IHF) is performed by a high-pressure pulse generated by the impact of the projectile on the closed liquid. The forming time is about 100-500 μs and the strain rate can reach $10^3\text{s}^{-1}-10^4\text{s}^{-1}$ in this process. The technology also has other advantages, such as reducing rebound, no sealing and high surface quality. It has good filling ability for parts with small geometry size. Therefore, IHF can solve the problem of the lack of formability in traditional hydroforming (HF) process, which is beneficial to manufacture parts with complex structure. Wang et al. [9] presented the impact hydroforming (IHF) and introduced the shock wave theory and used MSC to carry out finite element simulation. The pressure distribution changes in the depth direction, but not in the width direction. The impact hydroforming equipment is designed, which uses the energy generated by the compressed gas in the high speed cylinder to impact the liquid. IHF is different from traditional punching. There are both tensile stress and shear stress in IHF. Erkan et al. [10] worked on the determination of optimum sheet metal forming process and process parameters for various cross sectional workpieces by comparing the numerical results of high-pressure sheet metal forming, hydro-mechanical deep drawing (DD) and conventional DD simulations, which could help to select proper manufacturing process for a given workpiece geometry and understand the limitations of each sheet metal forming process. Tekkaya et al. [11] believes that pulse forming technology can solve some of these problems in order to solve the problem of complex component manufacturing for materials with difficult forming processes, including electromagnetic forming (EMF), electro-hydraulic forming (EHF) and impact hydraulic forming (IHF), etc. These methods have not been widely used in production. Ma et al. [12] designed an IHF device based on IHF principle, including forming area, energy area, acceleration area and control area, as shown in Fig. 2. The results show that IHF can improve the formability of low plasticity metals such as aluminum sheet at room temperature. It has successfully processed the complex aircraft aluminum parts with high drawing ratio and small fillet which can’t be realized by general hydraulic forming technology.
IHF has high impact energy and high forming limit, which is very suitable for the application of aviation industry. Khodko et al. [13] studied the characteristics of aluminum tubular blank free bulging during hydrodynamic forming; both experimentally, and through numerical finite element analysis using LS-DYNA, and obtained the quantitative description of a pressure wave in working liquid, which directly relates to the load on the blank. It is found that the propagation of the fluid pressure wave in the forming chamber leads to the diffusion of the wave like behavior of the circumferential strain. The alternating reflection of shock wave from the shaft ring and piston results in local increase of fluid pressure, which leads to greater deformation of the end of tubular billet.

Impact hydroforming technology is a high strain rate forming that can improve the limits of metal microplastic forming. The impact hydroforming uses water or oil medium instead of punch, which can overcome the defects of the general forming technology. In this work, the finite element method is proposed to study the impact hydraulic micro plastic forming process, analyze the formability of materials under high strain rate, and discuss the feasibility of impact hydraulic micro plastic forming.

2. Experimental setup
The impact hydraulic micro drawing forming model is established on the basis of the traditional model[14], and is modified on the basis of the traditional micro drawing composite model with punch, as shown in Fig. 3. In order to investigate the size effect in micro forming, there are three kinds of micro drawing composite forming models with different proportions adopted in this study. The three-dimensional model constructed by SolidWorks is mainly divided into four parts, including impact body, hydraulic cylinder, workpiece and lower die, as shown in Fig. 4.

The forming process is mainly divided into the following steps. Firstly, the impactor obtains the specified energy and speed under the impact of the projectile. This work simplifies the three-dimensional model, integrates the ejecta and the impactor, and keeps the outer diameter of the impactor consistent with the inner diameter of the hydraulic cylinder to ensure the sealing of the liquid. Under the impact
condition, the closed liquid can obtain high pressure pulse. Under the interaction of tensile and shear effects, the workpiece can realize micro deep drawing. During the whole forming process, the blank holder is loaded in the negative direction of Y axis to prevent the material edge from wrinkling. In order to simplify the calculation, considering the central symmetry of the model, the three-dimensional model chose its 1/4 part for simulation.

Fig. 4. 3D Model (a) impact body (b) hydraulic cylinder (c) workpiece (d) lower die

3. Results and discussion

3.1. Analysis of forming at an attenuated speed
With the initial speed of 100 m/s and the finite element post-processing of LS PrePost, the initial state and final forming state of the model are obtained, which is shown in Fig. 5. The change curve of the y-axis displacement of the center point with time is shown in Fig. 6. It is observed that the forming depth reached a large depth of 0.0444 cm at 8 μs. In the range of 0-4 μs, the forming rate is very high, and it is basically unchanged. After 4 μs, the forming rate decreased and then increased.

Fig. 5. Forming results (a) initial state (b) final state

With the initial speed of 100 m/s, from the center point along the radius direction, take 2 cells as the unit, select 22 points at five places respectively, and measure the thickness, as shown in Fig. 7. When the time is 0 μs, the initial thickness is 0.2cm. The thickness curve with time at 11 output points is shown in Fig. 8. It can be seen from the observation curve that the thickness thinning phenomenon
Fig. 6. Time-displacement curve of central point occurs in most places. The center point thinning is obvious, which is curve A. Two cells from the center point are curve B, and the thinning phenomenon along the radius direction is decreasing. The thickness changes at 4, 6, 8 and 10 cells from the center point are curves C, D, E and F, and the thinning phenomenon changes similarly along time. However, at 8 μs, the thinning phenomenon does not decrease along the radius direction, showing a trend of first decreasing, then increasing, then decreasing and then increasing. 12, 14, 16 and 18 cells from the center point are the areas with obvious bending and forming edge. Under the influence of the fillet radius of the lower die or the deformation of the mesh, position H shows a trend of thickening and is not used as a comparison curve. The thinning phenomenon of curves g and I decreases gradually along the radius direction. Curve I is 16 cells away from the center point, which is the forming edge. The liquid pressure is small, and it does not contact with the blank holder, and it is not affected by the blank holder. The thinning phenomenon is not obvious. There are 18 and 20 cells away from the center point, which are curves J and K. this area is the area of action with the blank holder. Under the influence of the load and friction effect of the blank holder, the trend is similar. Along the radius direction, the phenomenon gradually weakens. On the whole, the phenomenon of center point thinning is obvious, and gradually decreases along the radial direction, but it is not obvious in the edge area of forming area. Continue in the radial direction to the blank holder area. There is a strong thinning phenomenon in the blank holder region, which gradually decreases along the radial direction.

Fig. 7. Initial thickness of the part

Fig. 8. Thickness-time curve in 11 parts
It can be seen that in the process of micro drawing, the stress in different areas is different, and the equivalent stress is also different, and the effective plastic strain diagram at 4 μs and 8 μs is shown in Fig. 9. It can be seen from the diagram that during the forming process, the ball head part and the forming edge area contacting with the liquid are dangerous areas.

In the micro drawing, the deformation states of different regions are various, and the effective plastic strain can clearly reflect the deformation states of different regions. In Fig. 10, it is shown that during the forming process, large deformation occurs in the forming edge area, and at the end of the forming process, large deformation occurs in the ball head. Therefore, the forming edge area and ball head area contacting with liquid are dangerous areas.

3.2. Analysis of forming at different attenuated speeds

The y-direction displacement of the center point of the workpiece was taken as the ordinate and the time as the abscissa. Under the condition of different initial impact speed of 100 m/s, 120 m/s, 140 m/s, 160 m/s, 180 m/s and 200 m/s, the time-displacement curve is shown in Fig. 11. With all impact speeds, the workpiece has rebound effect. The larger the speed is, the more obvious the rebound effect is and the higher the forming limit is.
The fracture defect of the metal can be judged according to the thinning rate. At the speeds of 100m / s, 120m / s, 140m / s, 160m / s, 180m / s and 200m / s, the upper and lower points of the model center are selected, respectively. The distance between the two points is measured, and the thickness variation of the large thinning under different impact velocity is achieved as shown in Fig. 12. Generally, there is a fracture tendency when the thinning rate is over 20%, and there is no fracture tendency when the impact speed is between 100m / s and 140m / s, which is considered as the appropriate impact speed range.

3.3. Analysis of forming at a constant speed
A comparison between the forming result and the initial state at a constant impact speed of 100m / s was achieved. There is no obvious difference between the shape of workpiece impacted by initial velocity and that of workpiece impacted by initial velocity. It can be seen from Fig. 13 that the forming process is relatively stable when the impact is carried out at a constant speed, and the forming rate decreases and then increases at 6us. At 8us, the forming depth of the center point is 0.102cm.
22 points on the workpiece were chosen to measure the thickness variation along the radius direction from the center point. The change curve of thickness with time in 11 places is shown in Fig. 14. Compared with the initial velocity, the thickness reduction changes at 11 points are different under the condition of constant velocity. Under the same velocity, the thickness reduction is the most obvious in the central region. Under the condition of 100M / s and 8 μs, in Curve I, J and K, the large thinning rate is 36%, more than 20%, which has the risk of fracture. It can be considered to reduce the thinning rate by reducing the speed or the impact time.

When the workpiece is impacted at a constant speed of 100 m/s, the equivalent stress cloud chart of the workpiece is obtained at 4 μs and 8 μs, which is shown in Fig. 15. The results show that the energy is more concentrated and the deformation is more concentrated in the attenuation velocity mode, and the ball head part produces large equivalent stress. In the constant velocity mode, the energy distribution and the deformation is more uniform. The equivalent stress in the forming region is larger.

![Fig. 15. the equivalent stress cloud chart](image)

The equivalent plastic strain cloud chart of the workpiece is shown in Fig. 16. At 4 μs, there is no plastic deformation in the central region. Moreover, the deformation is evenly distributed. In the forming edge region, there are some local regions with large elastic-plastic deformation. At 8 μs, the deformation is spherical, and a large plastic strain occurs at the ball head. Compared with the attenuating velocity mode, the ball head does not deform much in the process of constant velocity forming, and the deformation profile is basin shape. The results of final deformation are the same, all of them are spherical, and the distribution of equivalent plastic strain is similar. All of them are larger in the forming edge area and ball head part.

3.4. Comparative analysis of different impact speed modes

The center point of the upper surface is selected and the time displacement curve of the center point under the impact speed of 100M / s under different speed modes is output as shown in Fig. 17. Compared with the forming depth of all element nodes, the constant velocity is obviously better than the attenuation velocity. As a result of overcoming resistance caused by impact by external force at a constant speed, including the interaction between water and water, a larger energy is generated and a larger forming limit can be achieved.

![Fig. 16. The equivalent plastic strain cloud chart](image)
In Fig. 18, the maximum thinning rate of constant velocity is 36% at 8 μs, which is 9% in attenuation velocity. The maximum thinning rate of constant velocity is more than 20%, and there is a risk of fracture, so the reliability of attenuation velocity is higher.

4. Conclusions

In this work, by establishing a three-dimensional model of impact hydraulic micro drawing process, microforming and impact hydroforming are combined as a new forming process. The simulation of impact hydraulic micro plastic forming at different speed mode is carried out. Under the condition of attenuation speed and constant speed, the forming time is rapid, both within 20 μs, which conforms to the characteristics of impact hydroforming.

- Under the condition of attenuation velocity, the deformation of workpiece increases with the increase of impact velocity. The workpiece yields and produces plastic deformation, and the forming edge area and ball head part have large stress. At the end of the forming process, the deformation of ball head is obvious, and the effective plastic strain distributions of other parts are the same.

- Under the condition of constant speed, the workpiece yields and there is plastic deformation. In the initial stage of the forming process, there is no plastic deformation at the center of workpiece. At the end of the forming process, there is large plastic strain in the edge region of the ball head and the forming edge region.

- Under the same initial impact velocity, the deformation and the thinning rate of workpiece in constant velocity mode is higher than that in the attenuation velocity mode.

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