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Finite element simulation analysis of the ultrasonic vibration forging of an aluminum cylinder workpiece

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Abstract

The propagation of high intensity ultrasonic wave in the solids can greatly affect the material properties. In this paper, the deformation characteristics of the ultrasonic vibration forging were investigated. For the ultrasonic vibration forging, the ultrasonic wave propagates in the specimen during the forming process. A detailed analysis and understanding of the mechanism of improvement is not possible on the basis of conventional experimental observations because ultrasonic vibration processing phenomenon occurs at a high speed. Hence, in order to study the mechanism of ultrasonic vibration forging, the finite element modeling was performed by using Abaqus/explicit. The metal flow of the ultrasonic vibration forging is totally different from the conventional one, and there is no "drum" effect in the forming process, which is the main characteristic in the conventional forging. Moreover, the stress and equivalent plastic strain distributions after the ultrasonic vibration forging process were explored.

Introduction

In the last 40 years, many studies have been done about the application of ultrasonic vibration in metal working process, such as cold and hot upsetting [1,2], deep drawing [3], wire drawing [4], sheet metal forming [5] and so on, moreover many review papers [6] about this project have been published. The difference between the conventional and the ultrasonic vibration metal forming is that the latter applied ultrasonic energy to act on the die and then uses the die to deform the workpiece. The advantages of the superimposed high-frequency vibrations onto the static load during the metal forming process are: a) reduce the forming force; b) decrease the spring-back angle during sheet metal forming and increase the forming limit of materials [1-6].

From all these published research papers, the reduction of the measured mean forming load can be attributed to the following mechanisms: the stress superposition (caused by the die vibration), absorption of acoustic energy at dislocations, reduction of internal and contact friction, and thermal effects. And some researchers also argued that there is a temporary softening of material properties during ultrasonic excitation on the lower die. In the recent research, Yusof [7] et al. investigated the ultrasonic compression tests by experimental and finite element (FE) methods. By adjusting the material properties and the friction coefficient during the moment of the ultrasonic excitation in the FE simulation environment, the stress-strain relationship predicted by the FE modeling was in a good agreement with that of the experiment.

For all these previous researches, the ultrasonic was just exerting on the lower or upper die, and there is no research to prove that the ultrasonic wave can propagate in the workpiece during the forming process. Ultrasonic energy is mechanical energy. When the wave transmits in the solid, it can disturb the particles of a body from equilibrium, which gives rise to internal forces that tend to return these particles to equilibrium. These internal forces per unit area are known as stresses. The stresses associated with the propagation of ultrasonic waves are the basic cause of the numerous mechanical effects attributable to applying ultrasonic energy [8,9].

In this paper, during the ultrasonic vibration forging process, the ultrasonic wave was directly injected into the workpiece. Due to it is really very difficult to get the real-time measurements of the forging phenomena during the application of ultrasonic vibration in the experiment, the FE method was applied as a main tool to investigate the deformation characteristic of the ultrasonic vibration forging. A commercial software, Abaqus/Explicit, is applied for the FE analysis in this study. Through the comparison of the conventional forging and the ultrasonic vibration forging, the metal flow, forming force, the stress and strain distribution of the ultrasonic vibration forging process were revealed.

1. Establishment of 2D FE model

Just one cross section of the workpiece was selected to do the analysis due to it is cylindrical and the 2D FE model created in the Abaqus as shown in Fig.1. The upper and lower dies were assumed to be rigid bodies, and modeled by an analytical rigid surface. Four-node bilinear quadrilateral plane strain with reduced integration and hourglass control elements (CPE4R) were applied to model the workpiece. The frictional behavior between the die and the workpiece is assumed to follow Coulomb's model. And the friction coefficient was set to 0.25 for a dry surface condition. The material properties of the soft aluminum grade (1050) were: Young's modulus E 69GPa, Poisson's ratio μ 0.33, density ρ 2719 kg/m^3. True plastic strain ε^{pl}, was defined using the following equation [7]:

$$\varepsilon^{pl} = \varepsilon^{t} - \varepsilon^{el} = \varepsilon^{t} - \frac{\sigma}{E}$$

where ε^{t} is the true total strain, ε^{el} the true elastic strain, σ the true stress.

In this study, the key point to create the FE model is the excitation of the ultrasonic vibration. Because the ultrasonic energy is mechanical energy, a pulse pressure $P_0 \sin wt$ was applied on the end of the workpiece. The method to exert the ultrasonic wave in the workpiece has been verified correctly in a previous study [10]. In this study, the frequency of the ultrasonic vibration is 20k Hz, so $w = 2\pi f = 125600$. And other process parameters are summarized in Table 1.

Table 1 Upsetting and ultrasonic vibration conditions

Dimension of the workpiece (mm)	Φ20×30
Upsetting speed, V (mm/s)	40
Frequency, f(kHz)	20
$p(t)$	sin(125600t)
Displacement of the upper die, S (mm)	10

2. Verification and evaluation of the developed 2D FE model

The accuracy of the FE model is very important for the numerical simulation. Therefore, the validity of the developed 2D FE model should be evaluated before we use it for the further study on the ultrasonic vibration forging process.

As a general rule, if the kinetic energy (ALLKE) of deforming materials does not exceed a small fraction (typically 5–10%) of its internal energy (ALLIE) throughout the most of the simulation process, moreover, if the two energy histories curves are smooth, the developed FE model can be considered to be valid. Fig. 2 shows the internal and kinetic energy histories of the deforming cylinder workpiece in the ultrasonic vibration forging process. It can be seen that the two curves are smooth. At the beginning of cold rotary forging, both the values of internal and kinetic energy are zero. With the increasing of the forming time, the value of internal energy increases gradually while the value of kinetic energy just increased a little and the value is closed to zero. In view of the rule, the developed 2D FE model of ultrasonic vibration is reasonable theoretically.

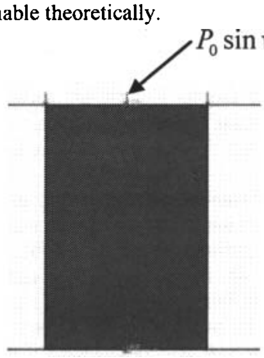


Fig.1. 2D FE model of ultrasonic vibration forging.

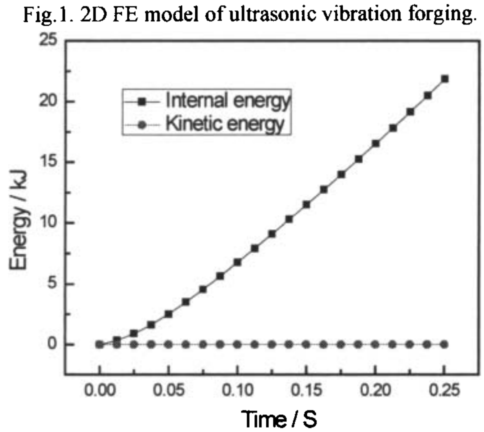


Fig.2. Energy histories of the deforming cylinder workpiece.

In order to verify the validity of the proposed 2D FE model experimentally, the simulation were compared with the research data obtained from Ref. [7], as shown in Fig. 3. In Ref. [7], the dimension of the workpiece was Φ8×8mm, the height reduction was 4mm, and the simulation was done in Abaqus software. The ultrasonic vibration was exerted on the lower die with the frequency of 20k Hz and the amplitude of 10μm. Here, in our paper, the simulation conditions for this comparison are the same as these in Ref. [7]. Moreover, the stress-strain relationship for the case of ultrasonic wave transmitted in the specimen during the forging is also presented in Fig.3. It can be seen from this figure that the simulation result of the stress-strain relationship for the ultrasonic vibration forging when the ultrasonic is exerted on the lower die is in good agreement with they reported in Ref. [7].

However, from this figure, when the ultrasonic vibration was exerted on the lower die, the path of the maximum oscillatory stress follows the path of the static stress-strain curve and that the path of the mean stress is lower than and parallel to the static stress-strain curve; when the ultrasonic wave propagate in the workpiece, the path of the maximum oscillatory stress will be parallel to, but can be higher than the static stress, referred to as overshoot. So, the way of the ultrasonic vibration excitation can affect the deformation process, and in the next section we will reveal the deformation characteristics of the ultrasonic vibration forging using this valid 2D FE model.

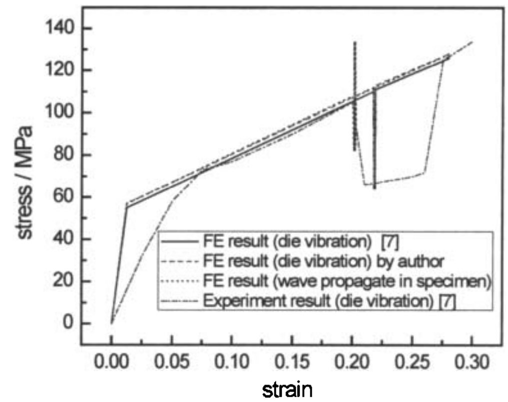


Fig.3. Comparison of the stress-strain relationship.

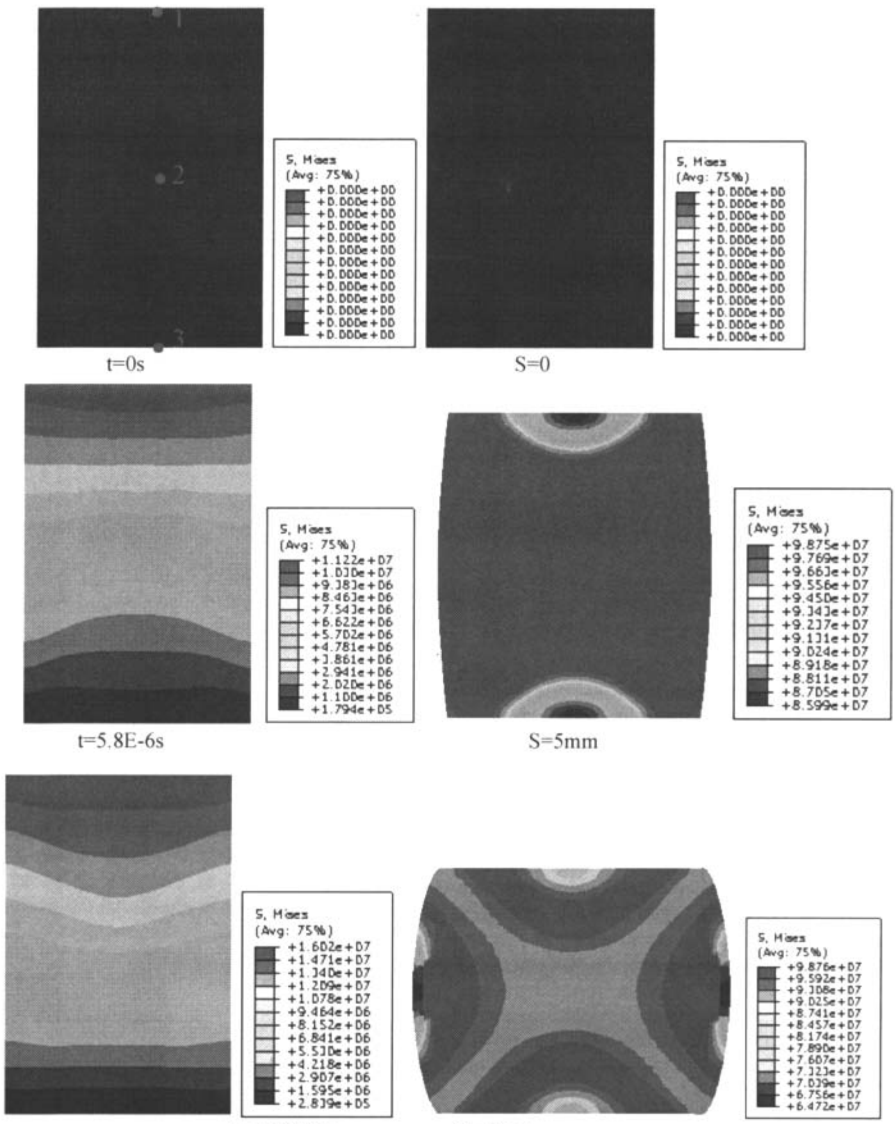
3. Results

4.1 stress field analysis

When the ultrasonic wave transmits in the material, it can create an additional stress field. Fig.4a shows the stress distributions when the wave propagates in the specimen. The velocity of the wave propagates in the specimen is $v = \sqrt{E/\rho} = 5037.6$ m/s, and the period $T = 1/f$ =5e-5. So, in a cycle, the wave can propagate $S = vT$ =0.2518m, and the height of the specimen is only 30 mm. At the time of t=5.8E-6s, the wave just reach the end of the specimen, and then it is reflected back and superimposed with the incoming one. At the time of t=1.16E-5 s, the first reflected wave reach the other side of the specimen, and then it is reflected, repeat again and again. Fig.5 shows the stress history for the points 1, 2, 3 defined in Fig.4a during the time of 2T. For point 1, which lies near the wave inputting side surface, the stress changing law just likes the input wave with the amplitude of 16.6MPa and the period of 0.25e-4 s. For point 2, which was in the middle of the specimen, in a cycle, there are several stress peak due to the stress superimposed. For point 3, at the end of the specimen, the stress is almost zero since the stress free for one side of the bar.

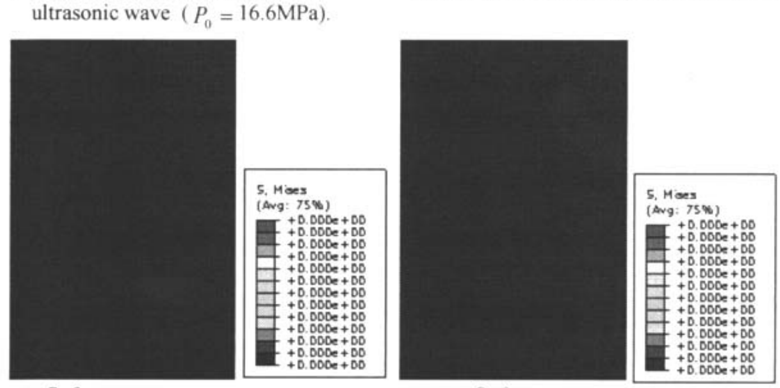
Fig.4b shows the typical stress distribution for the conventional forging process. Due to the friction force existed between the specimen and the die, the cylindrical workpiece exhibits the "drum" effect, which is the main characteristic of conventional forging process.

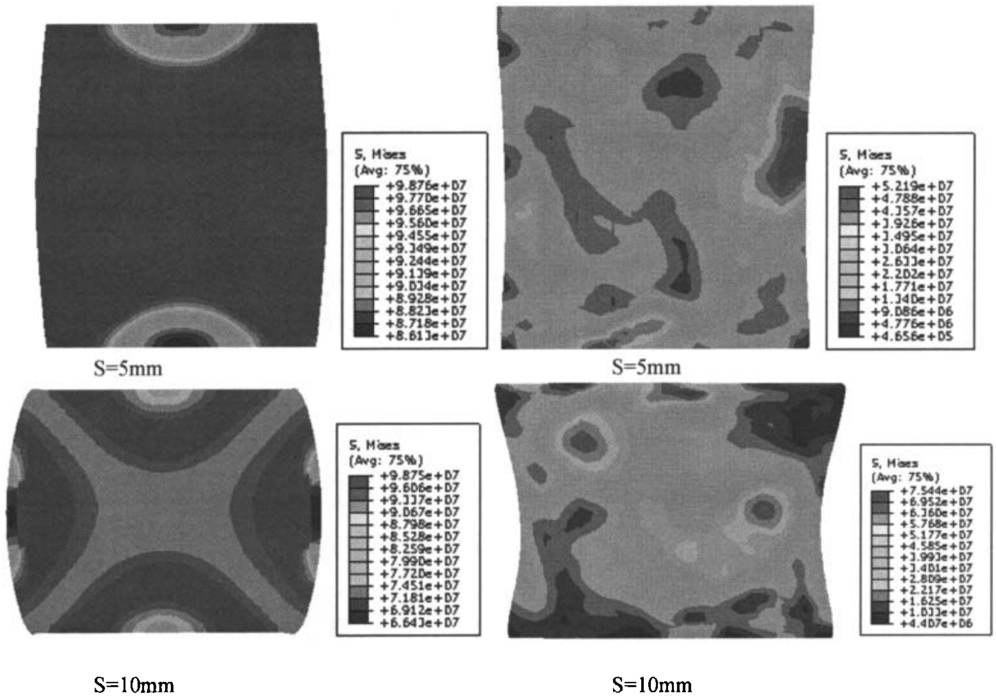
Fig.4c and Fig.4d show the stress distribution for the ultrasonic vibration forging processes but the values of the pulse pressure applied are different. During the compression process, if the extrusion speed is less than the maximum vibration speed, the die plates could be separated from the specimen, and the critical compression speed might be defined as $V_{cr} = 2\pi af$, a and f are the amplitude and the frequency of vibrations, respectively. The



(a)The stress field caused by ultrasonic wave ($P_0 = 16.6\text{MPa}$).

(b)Stress field caused by conventional forging





(c)Stress field caused by ultrasonic vibration forging (no-separated) (P_0 = 16.5MPa)

(d) Stress field caused by ultrasonic forging (separated) (P_0 = 16.6MPa)

Fig.4. Stress distributions during the forming process.

maximum vibration speed is just $2\pi af$ [11]. When P_0 = 16.5MPa (Fig.4c), the die plates does not separate from the specimen, the stress distribution is almost the same as the one of conventional forging and the workpiece also has the drum effect. If the pressure increased to 16.6 MPa (Fig.4d), the maximum vibration speed will also be increased, so the die plate separate from the specimen. In this condition, the stress distribution and the deformed shape of the specimen are totally different from the conventional one. The final shape of the workpiece looks like a reversed drum, where it is skinny in the middle and wide of the ends. For this forging process, the metal flow and deformation mechanism will be discussed in the following sections.

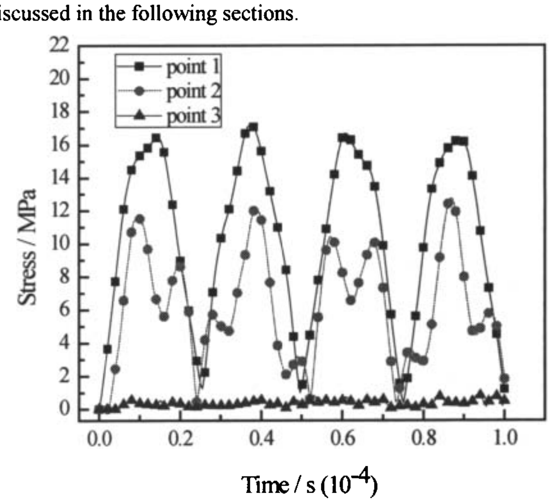


Fig.5. Stress history of the selected points.

4.2 The effect of ultrasonic vibrations on the metal flow.

In order to reveal the PEEQ distribution law in detail, some special points in the axial section of the cylindrical workpiece were selected as the tracking points for measuring the PEEQ values (shown in Fig.6). All the tracking points are located in the half of the axial section owing to the PEEQ distribution symmetry in the radial direction.

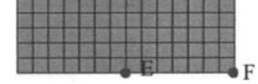
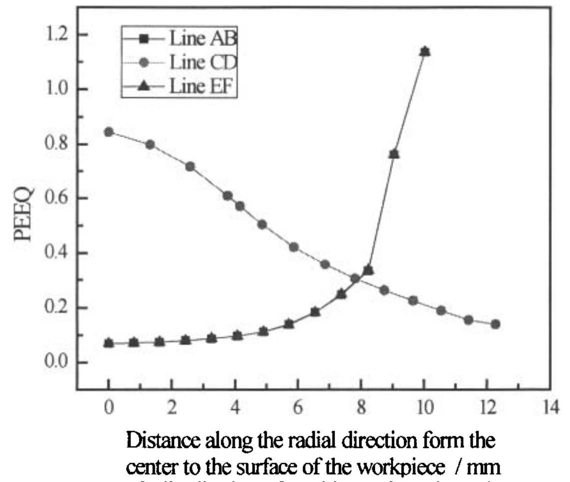


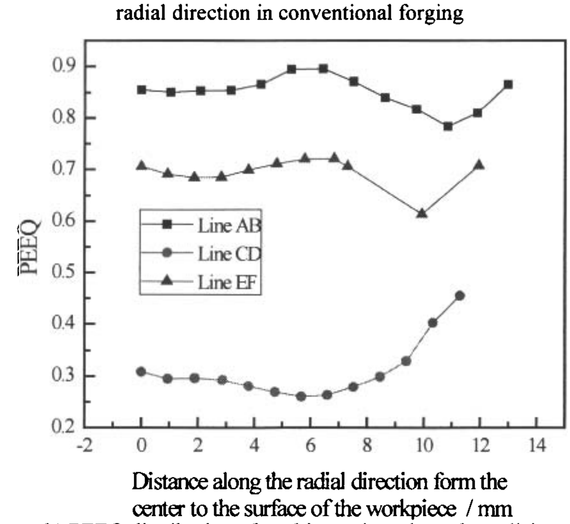
Fig.6. Tracking point in the axial section of the cylindrical workpiece.

Fig.7 illustrates the comparison of PEEQ distribution of tracking points along the radial direction between the conventional forging and ultrasonic vibration forging. It can be observed from Fig.7a that in conventional forging, the PEEQ value along A-B line and E-F line is identical, which coincides with the PEEQ distribution symmetry in the axial direction. Furthermore, the PEEQ value decreases along C-D line, while it gradually increases along A-B and E-F line. By comparing the three curves, it can be also concluded that the PEEQ value of the middle part is larger than that of the upper and lower region of the cylindrical workpiece. The maximum PEEQ value always lies in the center part of the cylindrical workpiece while the minimum PEEQ value always occurs in the upper surface and the lower surface during the conventional forging process.

In ultrasonic vibration forging (Fig.7b, the die plates separate from the workpiece), the PEEQ values along the line of AB and EF almost have no changes, they are around 0.85 and 0.7, respectively. It means that the deformation in the upper and lower surface is even, but the upper surface deformation is much more severe than that of the lower surface. The PEEQ in the middle of the workpiece is the smallest, along the line CD, the PEEQ gradually decreased firstly and then increased a little sharply.



a) PEEQ distribution of tracking points along the radial direction in conventional forging



b) PEEQ distribution of tracking points along the radial direction in ultrasonic vibration forging

Fig.7. Comparison of PEEQ distribution of tracking points along the radial direction between ultrasonic vibration forging and conventional forging.

4.3The effect of ultrasonic vibrations on the forming load

Fig.8 provides the force comparison between conventional forging and ultrasonic vibration forgings. From this figure, the force-displacement curve is really typical for the conventional forging process. At the beginning of the process, the forging force increases significantly from zero to a certain value. And then it gradually increases quasi-linearly. For the ultrasonic vibration forging, when the pulse pressure $P_0 = 16.5$MPa (the die plates contacted with the specimen), the force will also increase to a certain value at the beginning, which is almost the same as the conventional one, but then it increases with a cosine shape. It can be seen that, the mean force is equal to that of the conventional forging process. However, when the pulse pressure $P_0 = 16.6$MPa, the die plates separate from the specimen, so sometimes the force is zero. Moreover, the maximum force is much smaller than that of the two former forming processes. During the simulation process, if we save the data in each period of the pulse pressure, the final result data file will be very large and the total simulation time will be very long. So, just a short interval, from the displacement of 5mm to 5.08mm, was selected to analyses the force variation. From the small figure, the force varied sinusoidal.

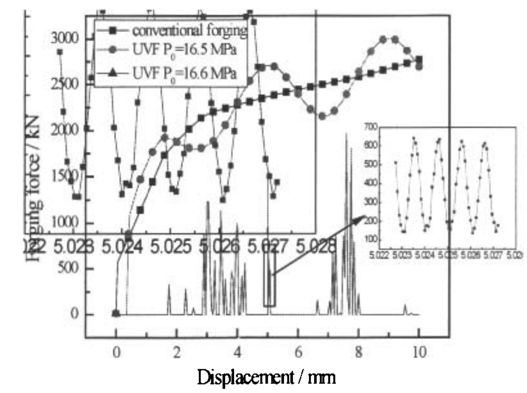


Fig.8. Force comparison between the conventional forging and the ultrasonic vibration forgings.

4. Discussion

5.1 vibration amplitude

In this study, when the pulse pressure P_0 is higher than 16.5MPa, the die plates separate from the specimen. Just as mentioned above, the critical compression speed might be defined as $V_{cr} = 2\pi af$, in which a is the amplitude. Fig.9 shows the particle vibration amplitude caused by different pulse pressures when there are no constrains at the top and bottom surfaces (for the point E). From this figure, we can get that the particle displacement increased with the increasing of the time, and the increased value is equal for each cycle. However, during the forging process, the workpiece will be constrained by the top and lower die plates, so the particle displacement cannot be infinite. From Fig.9, we can also get that, the bigger of the pulse pressure, the larger of the particle displacement will be. So, when the pulse pressure $P_0 = 16.6$MPa, the die plates will separate from the workpiece, but it will not be occurred when $P_0 = 16.5$MPa.

5.2 deformation mechanism

For the cylinder workpiece conventional forging, the drum effect will always be occurred due to the frictional force existed between the surfaces of the workpiece and the die plates as shown in Fig.10c. If there is no friction force between the surfaces of the workpiece and the die plates, the cylinder workpiece will keep the cylinder shape after the forging forming process (shown in Fig.10b).

In this study, when the die plates do not separate from the workpiece, the formed part has the drum effect (shown in Fig.4c), which means that the friction coefficient f is not zero. When the die plates separate from the workpiece, the final shape of the part looks like a reversed drum as shown in Fig.10d. As published in some older reports (the ultrasonic vibration was exerted on the die plates), when the workpiece did not separate from the die plates, the deformed parts had the drum effect even though the ultrasonic vibration upsetting can reduce the friction coefficient [2-5].However, if the workpiece separate from the die plates, during the forming process, the workpiece will vibrate and hit the die plates for 20 000 times per second, which just like that a hummer hit the workpiece continually with a frequency of 20k Hz. So, the final shape of the parts look like reversed drum.

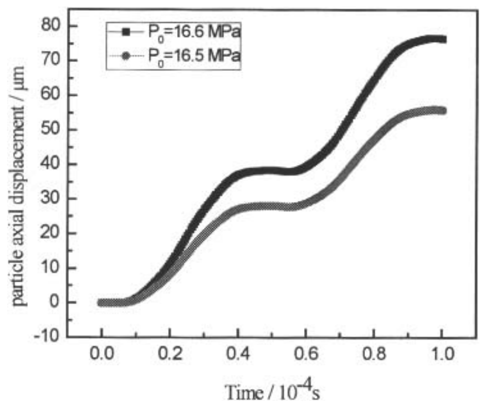


Fig.9. Particle axial displacement with the time in two cycles (Point E).

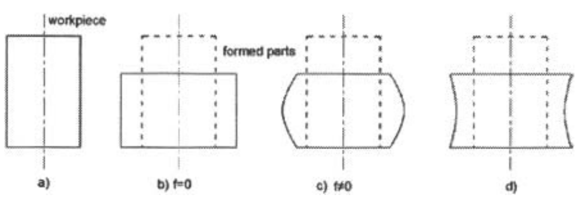


Fig.10. Schematic of the shape of the formed part after the forging process at different condition.

5. Summary

In this study, the ultrasonic vibration forging process was analyzed with the FEM method. Through the comparison of the ultrasonic vibration forging and the conventional forging, several important results were obtained just as shown in the follows.

(1) For the ultrasonic vibration forging, if the pulse press is over a critical value, the die plates will separate from the workpiece.

(2) If the die plates do not separate from the workpiece, the stress distribution and metal flow of the ultrasonic vibration forging is the same as that of the conventional forging, but the forming loads are different.

(3) If the die plates separate from the workpiece, the final shape of the formed part just looks like the reversed drum, however, the "drum" effect is the typical characteristic of the conventional forging. In this condition, the forming load is much smaller than that of the conventional forging.

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