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Research on the effect of ultrasonic vibration on the roll-over during the fine blanking process †

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Abstract

Fine blanking process as an advanced sheet metal cutting process has been widely used in industry. However, the roll-over of the parts fabricated by this process weakens the performance. For some parts, i.e. gear, the size of the roll-over should be very small in some situation. Therefore, a lot of efforts have been made to reduce the roll-over size or even eliminate the roll-over. Since the high frequency vibration can greatly change the metal flow, the ultrasonic vibration was applied into the fine blanking process to eliminate the roll-over in this paper. A finite element model was created to investigate the roll-over forming mechanism in the ultrasonic vibration assisted fine blanking process. The forming force, metal flow and mean stress were analyzed and compared with the conventional fine blanking process, and the roll-over size variation mechanism of the ultrasonic vibration assisted fine blanking process was revealed. An experiment of ultrasonic vibration assisted fine blanking has been carried out in this paper, and the roll-over size variation during the conventional and ultrasonic vibration assisted fine blanking process were compared. The results show that the experiment result has a good agreement with that of the finite element simulation. From this research, it can get that the ultrasonic vibration can greatly reduce the roll-over size, and it has a promising future to be used in the fine blanking process.

Keywords: Fine blanking; Ultrasonic vibration; Roll-over; Metal flow; Mean stress

1. Introduction

Fine blanking process is an effective and economical metal cutting process which can produce parts with clean-cut surface and high dimensional precision only in one operation. Therefore, fine blanking technology has been widely used in many industrial fields, such as in the machinery, automobile, aircraft and others. Especially in the automobile area, there are almost 100~200 fine blanking parts in a car.

The cutting surface feature of fine blanking parts contains the roll-over, clean-cut surface, crack and burr. Many researches have been done to investigate the forming mechanism of the roll-over, clean-cut surface and crack with Finite element (FE) and experimental methods [1, 2]. Chen [3] studied the shear band formation and propagation in fine blanking process. Thipprakmas [4] and Li [5] investigated the material flow during the fine blanking process. The results shown that the material nearing the cutting edge was pulled into the die cavity, and then the roll-over formed. Based on these researches, the fine blanking process can manufacture parts with almost full clean-cut surface with the optimized process parameters, but it cannot eliminate the roll-over completely which will weaken the parts performance. For some precision parts, such as gears, in order to eliminate the roll-over, they need to be machined after the fine blanking process, which increase the cost and reduce the production efficiency.

Many efforts have been done to reduce the roll-over size. Kondo developed an opposed die fine blanking process in 1977, in which the material was dual-directional extruded, and the roll-over of parts fabricated by this process is very small. However, the die structure and process design are very complicated, and it has not been widely used in the industrial area. Process parameters optimization can help to reduce the roll-over size. Kwak [6] studied the effect of the V-ring indenter on the size of roll-over, and found that increase the height of the V-ring indenter can reduce the width and the height of the roll-over. When the V-ring indenter gets close to the punch, the size of the roll-over will be decreased. Tanaka [7] studied the effect of die clearance on the size of roll-over, and the results show that the roll-over increases with the increasing of clearance. However, reduce the die clearance will make the material shear deformation to be much more severe and reduce the die life, and moreover it cannot eliminate the roll-

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over completely. Therefore, the high intensity ultrasonic vibration was applied into the fine blanking process in this paper with the purpose of eliminating the roll-over.

The ultrasonic vibration can change the metal flow during the plastic deformation. Because of the special volume effect and surface effect, ultrasonic vibration assisted metal forming process has a lot of advantages, such as reduce the forming resistance, and improve the material deformation ability. So far, the ultrasonic vibration has been applied in wire drawing [8], extrusion [9], upsetting [10], deep drawing and sheet metal forming process. Jimma [11] applied the ultrasonic vibration to the blank deep drawing process, and the experiment result shows that the axial vibration in the blank-holder or die plate can increase the Limiting drawing ratio (LDR), and the seasoning cracks of drawn cups can be avoided. Ashida [12] used the FE method to investigate the effect of the ultrasonic vibration on the stamping process, the simulation result shows that the ultrasonic vibration can avoid cracking and obtain large deformation. Inspired from these researches about ultrasonic vibration assisted sheet metal forming process, the ultrasonic vibration was applied into the fine blanking process.

In order to investigate the roll-over forming mechanism, a FE model of the Ultrasonic vibration assisted fine blanking (UAFB) process was created, and the experiment of the UAFB process has also been carried out. The results of this study indicated that ultrasonic vibration significantly reduces the roll-over size. The forming force, metal flow and mean stress were analyzed using the FE model, and the reason why the ultrasonic vibration can reduce the roll-over size was clarified.

2. The schematic of ultrasonic vibration assisted fine blanking process

The schematic of the ultrasonic vibration assisted forming process is shown in Fig. 1. The ultrasonic generation system includes the ultrasonic generator, transducer, the amplifier and the punch. The eigenfrequency of the punch should be equal to the ultrasonic vibration frequency. The ultrasonic vibration is amplified by the amplifier and injected into the punch, then the particle on the surface of the punch will be vibrated with the amplitude of a.

The Conventional fine blanking (CFB) process generally includes the punch, die, blank holder and counterpunch. During the fine blanking process, the billet is put on the die firstly and the blank holder presses the billet tightly. Then, the punch moves down and at the same time the counterpunch press the billet tightly. Under the action of the punch, blank holder and the counterpunch, the materials in the shear zone kept the state of compressive hydrostatic stress and separated. For the UAFB process, the ultrasonic vibration was injected to the punch, and the top surface of the punch was vibrated with the amplitude a (as shown in Fig. 2). Therefore, during the UAFB process, the punch moves down and the top surface of the punch vibrates with the amplitude a at the same time. Compared with the CFB process, the additional punch surface vibration will change the material flow during the UAFB process.

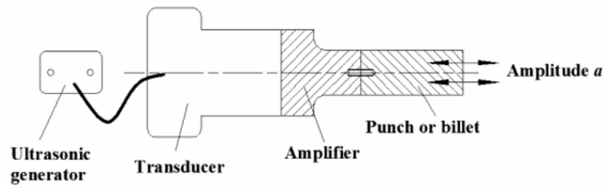


Fig. 1. Schematic of the ultrasonic assisted metal forming processing.

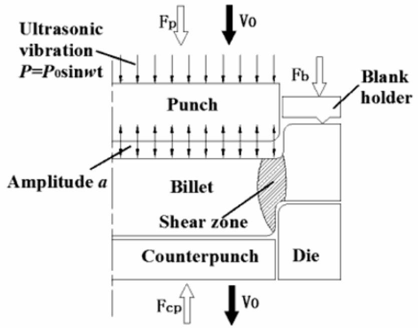
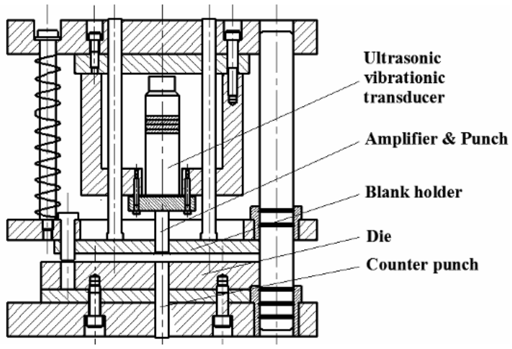


Fig. 2. Schematic of the ultrasonic vibration assisted fine blanking process.

3. The experimental procedure and the FE model

3.1 Experimental procedure

The experiment of the UAFB process was carried out in this paper. A hydraulic fine blanking press machine with the model of YJT26-160 was applied. The total capability of the press is 1600 kN, the blank holder cylinder is embed in the main slide block with the capability of 800 kN, and the counter punch cylinder is embed in the lower workbench with the capability of 800 kN. The blank holder force and the counter punch force are adjustable in this machine, and were set to 25 kN and 12.5 kN, respectively. The ram speed was 50 mm/s in this research. The schematic of the UAFB process equipment is shown in Fig. 3(a). The ultrasonic vibration transducer contacted with the amplifier tightly. In order to reduce the total height of the ultrasonic vibration generation system, the amplifier and the punch was design as one part. In this experiment, the ultrasonic vibration path is sine wave, and the vibration amplitude can be adjusted by changing the output power of the ultrasonic vibration generation unit. In this work, the maximum output power of the unit is 1500 W. The vibration amplitude is measured by the measuring apparatus, and the vibration amplitude was about 20 μm used in the experiment when the output power is 1125W (75 % of the maximum output power). Therefore, the vibration amplitude was set to 20 μm in the FE model. The output frequency of the ultrasonic transducer is 20 kHz. A rubber pad was put between the punch and the container to avoid the vibration being propagated to the container to ensure the vibration system to



(a)

(b)

Fig. 3. (a) The schematic; (b) the photograph of the equipment for the UAFB experiment.

be worked properly. Moreover, the clearance between the punch and the die was set to 0.02 mm (1 %t). The photograph of the UAFB equipment is shown in Fig. 3(b).

In this experiment, the 1045 carbon steel which spheroidizing annealed was used as the billet material. The workpiece is a circular plate, the diameter is 10 mm and the thickness is 2 mm. During the UAFB experiment, the ultrasonic vibration system was started firstly and then started the fine blanking press machine.

3.2 FE model

A commercial software, Deform 2D, was used to analyze the forming process of the UAFB and CFB process. Since the billet was axial symmetric, a 2D axial symmetry model was created to simplify the FE model and to improve the computation speed as shown in Fig. 4.

The key problem for the FE model of the UAFB process is about how to apply the ultrasonic vibration into the punch. As mentioned in Sec. 2 and in the UAFB experiment equipment, when the ultrasonic vibration injects into the punch, the bottom surface of the punch will be vibrated with the frequency of f and the amplitude a, and the punch also moves down. However, in the software of Deform 2D, the punch was set to rigid, it cannot be set the movement boundary conditions of vibration and moving down at the same time. Consideration that the material separation was caused by the relative motion of the punch and the die during the fine blanking process, the punch was only set to be periodic vibrated and the die moves up with a speed of 50 mm/s in the FE model as shown in Fig. 4. Although the punch and die movement situation in the FE model is different from that in the experiment, it can also accurately predict the UAFB process.

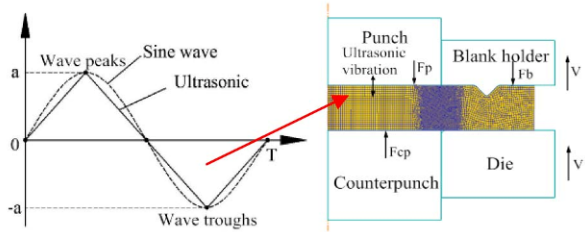


Fig. 4. The FE model of the UAFB process.

In this model, the counterpunch presses the billet with the force of F_{cp}, the blank holder holds the billet with the force of F_b and moves up synchronously with the moving of the die. The blank holder force F_b was calculated by the following equation:

$$F_b = 4L_e h\sigma_b \quad (1)$$

where L_e is the v-ring indenter circumference, h is the v-ring indenter height and the σ_b is the tensile strength of the billet. The blank holder force was calculated to about 25 kN, and the counterpunch force was set to 0.5 F_b, which is 12.5 kN in this model.

In order to comprehensively analyze the whole deformation process, it has to save computation data in every vibration period of the punch. In this paper, the vibration frequency f is 20 kHz, so the period $T = 1/f = 0.05$ ms. In order to record the whole UAFB process and reduce the computation time, the computation data was saved in four key points in very vibration period as shown in Fig. 4. Therefore, the minimum time step is 0.0125 ms, and the total time step which set in the Deform is 4000.

In this FE model, the punch, die, blank holder and counterpunch were all assumed to be the rigid. It is known that the clearance between the punch and the die is very small during the fine blanking process. Therefore, the deformation area is very narrow, and the material deformation in shearing zone is almost the pure plastic shear deformation. So, in order to simplify the FE model and save the computation time, the elastic deformation was ignored and the rigid plastic material model was applied. The rigid plastic material model has been widely used in the fine blanking modeling process as shown in the other literatures [2, 13] and good results have been obtained. The billet material was AISI1045, and the material property can be expressed by the constitutive equation as shown in Table 1. The rectangular elements were applied to model the billet, and the density of the meshes in the shearing zone is greater than that of other zones. In order to avoid the mesh

Table 1. Dimensional information for the FE model and process parameters of the fine blanking process employed in this study.

Name	Description
Parts types	Billet: Plastic punch/die/blank holder/count punch: Rigid
Billet material	AISI1045 (t = 2 mm) $\bar{\sigma} = 239.7\bar{\varepsilon}^{0.3577} + 629.4$
Tool cutting edges	Punch fillet radius $R_p = 0.02$ mm, Die fillet radius $R_d = 0.2$ mm
Blanking clearance	1 % t
Blank holder force Fb	25 kN
Counterpunch force Fcp	12.5 kN
Die moving up speed	50 mm/s
Friction coefficient	0.1
Fracture criterion equation	Oyane $C = \int_0^{\bar{\varepsilon}_f} \left(1 + a_0 \frac{\sigma_m}{\bar{\sigma}}\right) d\bar{\varepsilon}$
Critical fracture value Vibration frequency f	2.5 20 kHz
Vibration amplitude	0 for CFB 20 μm for UAFB

distortion, the mesh self-adaptive technology was used for the element in the shearing zone. The fracture criterion used in this paper is the Oyane criterion which considered the effect of the hydrostatic stress and stress tri-axiality $\sigma m/\bar{\sigma}$ on the crack initiation. This criterion can predict the crack initiation and propagation successfully during the fine blanking process, which has been valid in many researches [14, 15]. Hambli [16] and Zhao [17] compared several fracture criterions in his research, and found that when the criterion fracture value is 2.455, the Oyane criterion can predict the fracture failure during the blanking process very well. Therefore, the critical fracture value of the Oyane criterion was set to 2.5 in this research. For the friction coefficient, consideration that it is 0.1 for the fine blanking process [2] also for the ultrasonic assisted upsetting [18] and compressing process [19], the friction coefficient was set to 0.1 in this research. The dimensional information for the FE model and process parameters of the fine blanking process employed in this study were summarized in Table 1.

4. Results and discussion

4.1 The effect of ultrasonic vibration on the blanking force

Fig. 5 shows the simulation results of the punch force in the CFB and UAFB process. In the CFB process, when the punch started to cut the billet, the punch force increased rapidly. With the increasing of the die stroke, the punch force increased to a peak, and then decreased gradually. In the UAFB process, the variation trend of the maximum punch force is similar to that of the CFB, but the UAFB punch force is fluctuated. In order to reveal the force fluctuation during the UAFB process clearly, the force variation during a small time interval from 50.3 ms to 50.8 ms was analyzed as shown in Fig. 6.

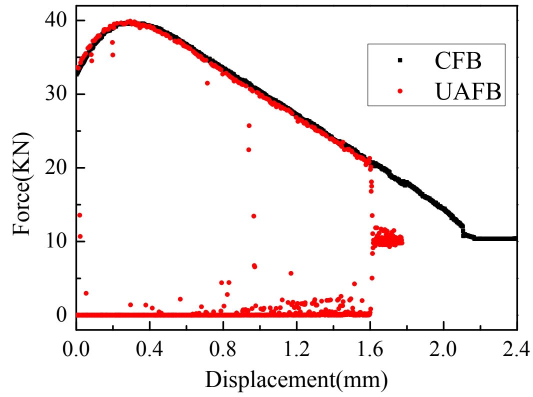


Fig. 5. Punch force versus displacement for these two forming processes.

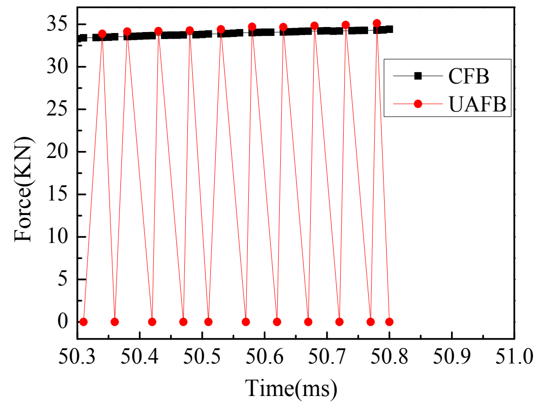
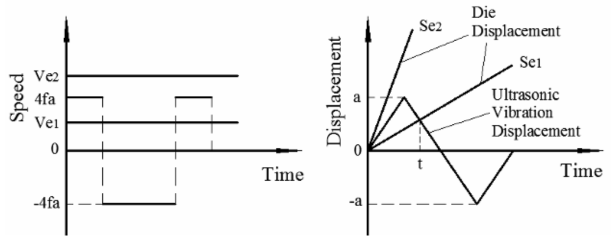


Fig. 6. Fluctuation of punch force due to the vibration.

In this work, the vibration period T = 0.05 ms. The time internal selected in Fig. 6 includes 10 periods (△t = 10T). From Fig. 6, the punch force is fluctuated cyclically in the UAFB process, the maximum punch force in the UAFB process is approximately equal to the punch force in the CFB process and the minimum punch force is zero. This means that the punch contact with and separated from the billet in every period when the ultrasonic vibration was applied on the punch.

The reason for the phenomenon of the separation and contact between the punch and the billet is the relative cutting velocity is totally different from that of the CFB process. Liu et al. and Mousavi et al. have done researches about the speed of ultrasonic vibration assisted upsetting and extrusion deformation, respectively [20, 21]. In this work, ultrasonic vibration was applied on the punch. In the CFB process, the billet contacted with the punch, the punch was stationary while the die moved up, which result in the relative movement between the punch and the die so that the punch can cut the billet. The cutting speed is equal to the die moving up speed. However, during the UAFB process, the actual cutting speed (V_r) can be separated into two parts, the die moving up speed (V_e) and the punch vibration speed ($V_{au(t)}$), and these speeds have to obey



(a) (b)

Fig. 7. The UAFB speed and displacement diagram: (a) Variations of fine blanking and vibration speed; (b) variations of punch and die vibration displacement.

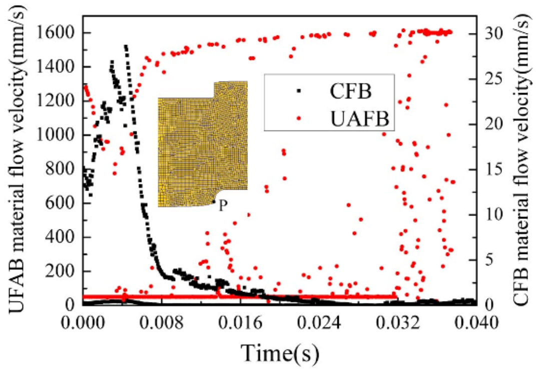


Fig. 8. The metal flow velocity variation at point P for the two forming processes.

the Eq. (2):

$$\vec{\mathbf{v}}_r = \vec{\mathbf{v}}_e + \vec{\mathbf{v}}_{au(t)} \ . \qquad (2)$$

Based on the published literature, if the die moving up speed is smaller than the vibration speed ($V_{e1} < V_{au(t)}$) (shown in Fig. 7(a)), the punch displacement is greater than the die displacement (the die moving up speed V_{e1} corresponding displacement is S_{e1}), so the billet would separate from the punch between time 0~t (shown in Fig. 7(b)); when the die moving up speed is bigger than the vibration speed ($V_{e1} > V_{au(t)}$), and the billet would contact with the punch. In this work, f = 20 kHz, a = 20 µm, the displacement is $f(t) = 4aft$ (in the time of 0-T/4), so the critical vibration speed would be equal to $Vau(t) = f^{'}(t) = 4af = 1600\ mm/s$. In this research, the die moving up speed is much smaller than 1600 mm/s. Therefore, the billet contacted with and separated from the punch in every cycle during the UAFB process, and this deformation type belongs to the high impacting forming process.

4.2 The effect of ultrasonic vibration on the material flow

According to the roll-over formation mechanism, the roll-over formation is closely related with the materials flow. The roll-over is formed on the outer contour of parts, and the diameter of the part is 10 mm. Therefore, the point P with the coordinate (4.99,0) that located on the outer contour of parts

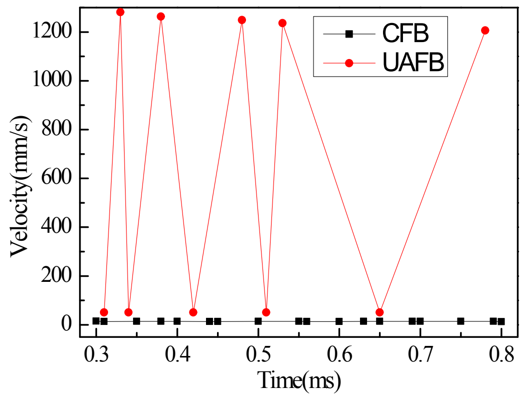


Fig. 9. The metal flow velocity fluctuation diagram.

was selected to analyze the metal flow as shown in Fig. 8.

Fig. 8 shows the metal flow velocity variation at point P for the two forming processes. In the CFB process, the metal flow velocity in the roll-over zone increased firstly and then decreased between the blanking time of 0 to 0.01 s. After the time of 0.01 s, the velocity almost has no changes, which means that the formation of the roll-over just happens at the beginning of the blanking and in a very short period of time. In the UAFB process, the metal flow velocity of the roll-over zone is fluctuated and the flow velocity reaches to as high as 1600 mm/s. As mentioned in Sec. 4.1, the maximum punch vibration speed (V_{au}) is 1600 mm/s. Therefore, the velocity of the material impacted by the punch can reach to so high. The metal flow velocity in CFB process is much smaller than that in the UAFB process, the maximum metal flow velocity in CFB process is only about 28 mm/s. This means that ultrasonic vibration can improve the metal flow velocity and make the material deformation much more severe in the shearing zone.

In order to reveal the metal flow velocity variation clearly for the UAFB process, a short time interval △t = 0.5 ms(△t = 10T) was selected to do the analysis as shown in Fig. 9. From Fig. 9, it can get that the metal flow velocity is fluctuated cyclically for the UAFB process, and the minimum metal flow velocity in the UAFB process is also greater than that in the CFB process.

During the UAFB process, the material flow direction was also periodicity changed. Table 2 shows the material flow velocity distribution in the shearing zone during the UAFB process. From this table, it presents that in a very short time, such as in 2 ms (from 0.00207 s~0.00209 s), the materal flow direction changed. At the time of 0.00207 s, the material flowed up and the material flow velocity reached the minimum, and at the time of 0.00209 s, the material flowed down and the material flow velocity reached to the maximum. The changing of the material flow velocity happened during the whole UAFB process. However, in the CFB process, the material in the shearing zone just flowed up and the flow direction did not changed as shown in Table 3. As discussed in the Sec. 4.1, the billet contacted with and separated from the

Table 2. The metal flow velocity distribution in shearing zone during UAFB process.

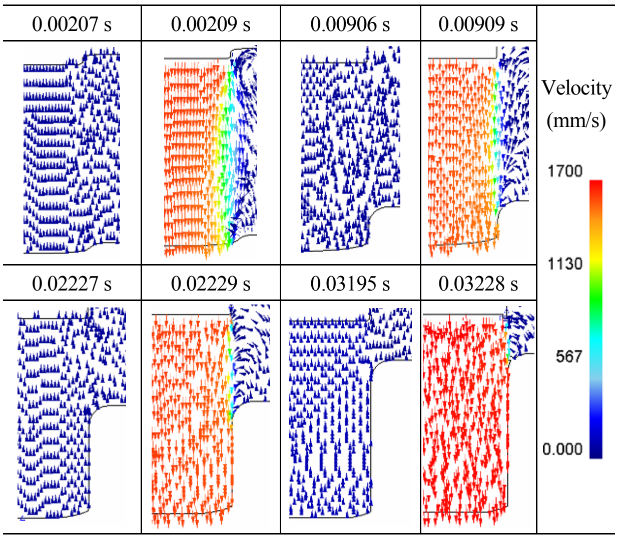
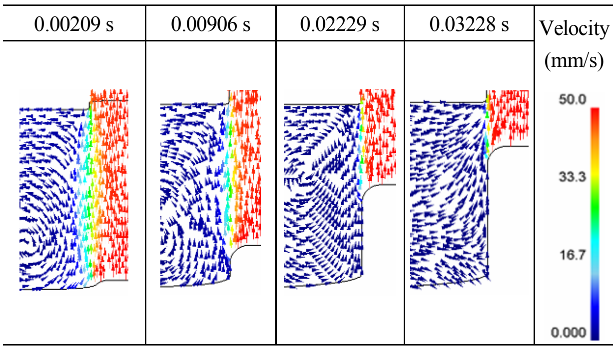


Table 3. The metal flow velocity distribution in shearing zone during CFB process.



punch in every cycle in the UAFB process. When the billet separated from the punch, the material in shearing zone flowed up, when the billet contacted with the punch, the metal in shearing zone flowed down. This means that ultrasonic vibration changed the material flow direction in the UAFB process.

The changing of the material flow caused by the ultrasonic vibration affects the size of the roll-over greatly. Fig. 10 shows the roll-over of the part formed by CFB process and the UAFB process. The width and the height of the roll-over for the CFB process are 0.679 mm and 0.132 mm, respectively, and for the UAFB process, they are 0.035 mm and 0.056 mm respectively, which is almost close to zero. The roll-over size in UAFB process is much smaller than that in CFB process. Therefore, ultrasonic vibration can reduce the roll-over size and almost eliminate the roll-over of the fine blanking parts.

Moreover, the roll-over size is changeable during the whole UAFB process as shown in Fig. 11. In the CFB process, the roll-over width and height increased firstly and then remained unchanged after the die displacement of 0.3 mm, which proved that the roll-over just formed at the beginning of the

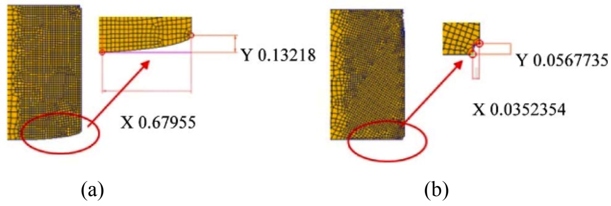


Fig. 10. The size of roll-over: (a) In the CFB process; (b) in the UAFB process.

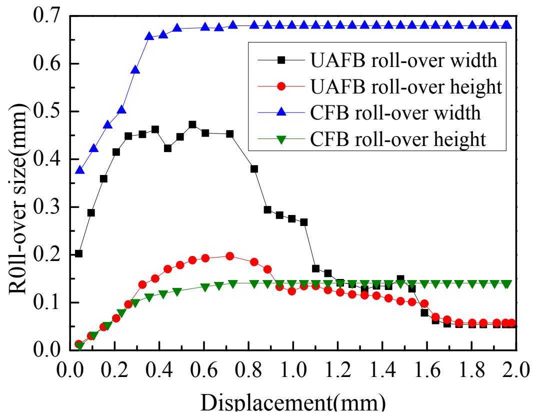


Fig. 11. The roll-over size variation during the whole fine blanking process.

blanking process. However, in the UAFB process, the roll-over width and height increased firstly and then decreased gradually, which means that the roll-over just formed at the beginning and then decreased because of the changing of the material flow caused by the ultrasonic vibration. That is because the ultrasonic vibration assisted plastic forming process belongs to the high-frequency impacting deformation. As shown in Table 2, the velocity of the material in shearing zone flowed down is much larger than that flowed up, and the material was impacted into the outer contour of parts gradually during the process of the punch separated and contacted with the fine blanked part after the roll-over was formed, and then the roll-over size reduced gradually.

4.3 The effect of ultrasonic vibration on the mean stress

Fig. 12 shows the mean stress distributions when tensile stress just appeared in the roll-over area during the CFB process. In the roll-over area, the mean stress was the tensile stress, and decreased from roll-over side to the burr side (from point 1 to point 2 as shown in Fig. 12). At the burr side, the mean stress was the compressive stress. Roll-over formation depends on the tensile stress state, when the material mean stress changes from tensile stress to compressive stress, the formation of roll-over will be ceased. That is because the material was extruded into the die during the fine blanking process. At the beginning of the FB process, the material flow was impeded by the die, and the material bear the tensile stress. Therefore, the material flow velocity at the outer contour of

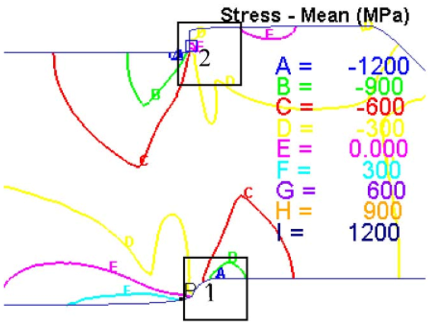
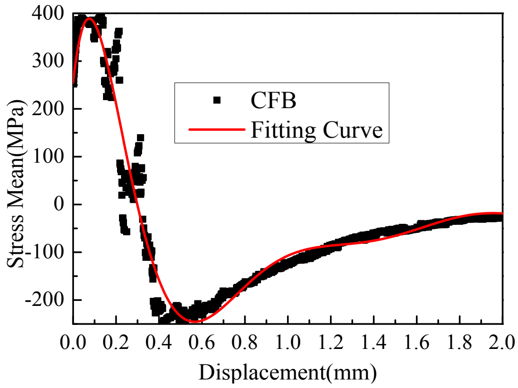
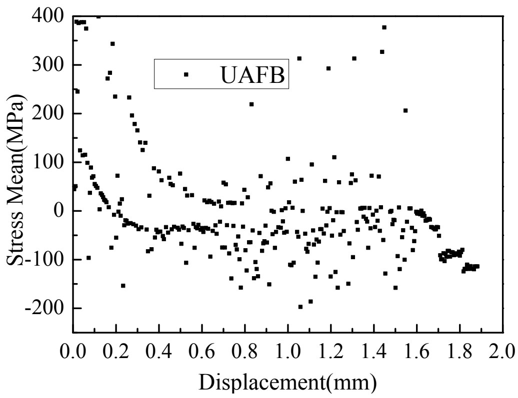


Fig. 12. The material mean stress distributions in the CFB process.



(a)



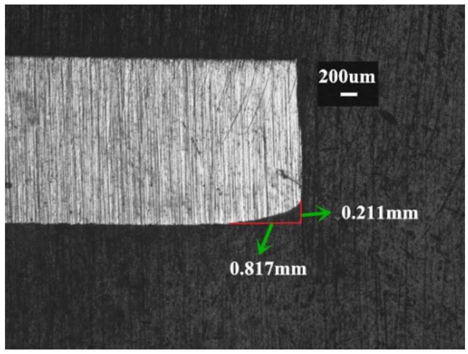
(b)

Fig. 13. The material mean stress distributions: (a) In the CFB process; (b) in the UAFB process.

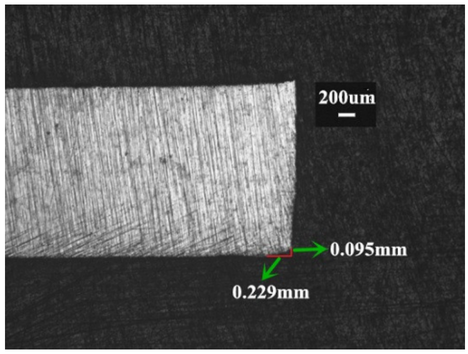
parts is smaller than that in the center, and the roll-over formed.

Fig. 13(a) shows the mean stress variation of the material in point 1 during the whole CFB process. By observing the fitting curve, the material was in the tensile stress state firstly. The tensile stress increased firstly and then decreased, and the stress state of the material was changed from the tensile stress to the compressive state at the displacement of 0.3 mm. After that, the material was kept in the compressive state. As mentioned in Fig. 11, at the displacement of 0.3 mm, the roll-over size tends to be unchanged in the CFB process. It validates that when the material mean stress is tensile stress, the roll-over starts to form; after the mean stress turning into compressive stress, the roll-over stops to form.

Fig. 13(b) shows the mean stress variation of the material in point 1 during the whole UAFB process. When the ultrasonic vibration was applied on the punch, the mean stress of the material in point 1 changed severely during the whole deformation process. The mean stress sometimes was tensile stress and sometimes was compressive stress. Due to the high frequency changing of stress state, the material flow has been changed and the roll-over size changed during the UAFB process.



(a)

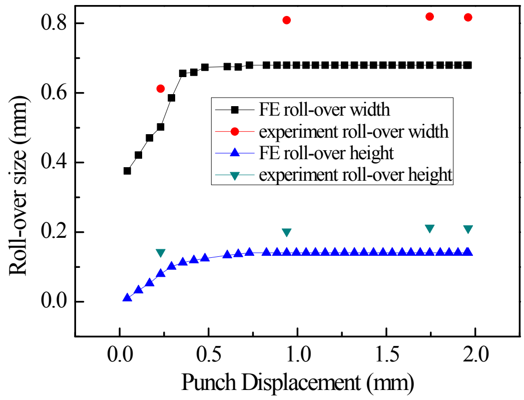


(b)

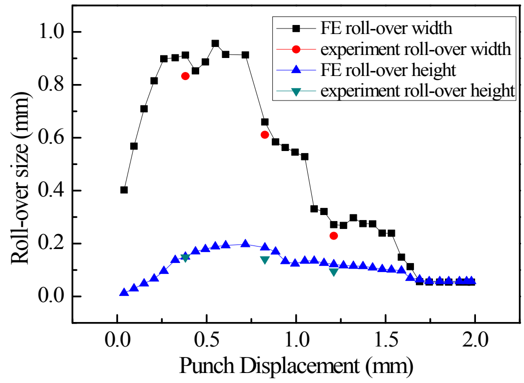
Fig. 14. The roll-over size: (a) In the CFB experiment; (b) in the UAFB experiment.

4.4 Comparison of the size of roll-over between the FE simulation and experiments

Fig. 14 shows the roll-over size of parts formed in the CFB and UAFB experiments. The process parameters were the same as that in the FE simulation. In the CFB experiment, the roll-over width and height were 0.817 mm and 0.211 mm, respectively. The experiment result has a good agreement with that of the FEM simulation. In the UAFB experiment, the roll-over width and height are 0.229 mm and 0.095 mm, respectively. The result error between the experiment and the simulation is a little large for the UAFB process. That is because the ultrasonic vibration unit was always out of works when the punch penetration was about half thickness of the billet since the fine blanking force was a little big during the UAFB experiment. Therefore, the roll-over size of the experiment part



(a)



(b)

Fig. 15. Roll-over size comparison between the FE simulation and experiment result at different punch displacement: (a) CFB process; (b) UAFB process.

is close to the simulation result at the displacement of 1.3 mm as shown in Fig. 11. In order to reveal the changing of roll-over size during the blanking process, the roll-over size at different punch displacement were measured and compared with the simulation result as shown in Fig. 15. Because the hydraulic press is difficult to be stopped at the required position, the punch stopped displacement is different between the UAFB and CFB process. The roll-over changing trend of the experiment result has a good agreement with that of the simulation result. Moreover, from the experiment results it can get that the size of roll-over in the UAFB process is much smaller than that in the CFB process, which demonstrates that the ultrasonic vibration can reduce the roll-over size. In the future, the authors have to improve the ultrasonic vibration unite and make it to be worked well during the whole UAFB process.

5. Conclusions

In this study, the ultrasonic vibration was applied in the fine blanking process. The formation mechanisms of the roll-over in the CFB and the UAFB process were analyzed with FE simulation and experiment method. From this study, the following conclusions were arrived at:

(1) The roll-over size of the parts formed by UAFB process is much smaller than that of the CFB process. The ultrasonic vibration can almost eliminate the roll-over of the fine blanking parts.

(2) The roll-over was formed in a very short period of time at the beginning of the fine blanking process. When the ultrasonic vibration was applied in the fine blanking process, the material flow was significant changed. The material would impact into the roll-over zone during the whole blanking process, and the roll-over size of the part was gradually decreased.

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