Numerical analysis of sheet metal U-Bending process

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Abstract

The sheet metal U-bending forming is a complex process, based on the assumption of Prandtl-Reuss flow rule and Von Mises yield criterion, the incremental elastoplastic large deformation finite element model was established based on the Updated Lagrangian Formulation (ULF). The elastoplastic conversions of boundary and deformation are reduced with rmin rule. The friction phenomenon of slippage and viscosity at the boundary interface is revised with increment of revision Coulomb rule. The increment rules are led into the whole stiffness matrix, and derived out the stiffness equation. The studies show that the influence on U-Bending deformation of sheet metal is influenced by die structure and parameter. The results show there is a good consistency between the finite element simulation and experimental result.

Keywords: elastoplastic, FEM simulation, sheet metal, U-Bending, warpage

1 Introduction

Sheet metal forming is a common material processing method, which can be divided into several kinds, such us: stretching, bending, drawing and flanging, etc. Bending is the important forming that pushes sheet mental into a certain shape with different angle and curvature. Bending sheets is commonly used in the area of sheet metal forming, especially in the automotive metal, industrial products and household appliances. The common types of bending are V-Bending, U-Bending and L-Bending [1].

There are some problems in U-Bending, such us thinning, thickening or warping, and unable to obtain the desired shape [2, 3].

In this paper, based on the axisymmetric large deformation elastic-plastic theory to analyse the U-bending of sheet metal, the relationships between the U-Bending quality and parameters are analysed such us: punch die radius, clearance, friction coefficient and plate thickness etc. Finally, the theoretical analysis is verified with the experimental results.

Kim and Thomson [4] found that spring-back and the sidewall curl were proportional to die radius, die clearance, work hardening rate and yield strength after considering the friction factor in U- bending

Lee and Yang [5] analysed U-draw bending process parameters with the finite element method, such us: punch velocity, penalty function, damping ratio, and evaluated the important factor which influencing the spring-back with the taguchi method, and found the element size and arc radius were the significant factor.

Liu [6] analysed U-draw bending spring-back under the variable and fixed plate force with the NUMISHEET93 method, and found the variable power can obtain the better forming quality.

Huang and Chen [2] developed a set of incremental elastic-plastic large deformation finite element program to simulate the V bending spring-back and saddle phenomenon and verified experiment.

Sousa [3] optimized design parameters of V and U bending with the finite element method and Genetic algorithm (GA), those parameters including: punch and die radius, punch displacement and plate force.

2 Experimental Section

2.1 FUNDAMENTAL THEORY

2.1.1 Virtual work principle

It descripts the elastic-plastic deformation with the updated Lagrangian formulation ULF [10], the Virtual work principle formulation can be shown as follows:

$$\int_{V^E}\left(\ddot{\sigma}_{ij}-e\sigma_{ik}\dot{\varepsilon}_{kj}\right)\delta\dot{\varepsilon}_{ij}dV+\int_{V^E}\sigma_{jk}L_{ik}\delta L_{ij}dV=\int_{S_f}\dot{f}\,\delta v_i dS\,, \quad (1)$$

where, $\ddot{\sigma}_{ij}$ is the Cauchy stress tensor, $\dot{\varepsilon}_{kj}$ is the rate of stress tensor, $\dot{\varepsilon}_{ij}$ is the strain tensor, σ_{jk} is the rate of strain tensor, $\delta\dot{\varepsilon}_{ij}$ is the virtual strain tensor of the point, δL_{ij} is the virtual velocity gradient tensor of the point, δv_i is the velocity component, $\dot{f}$ is surface force component, L_{ij} is velocity gradient tensor, V is unit volume, S is unit surface area.

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2.1.2 Constitutive relation

In preparing the theory of elasto-plasticity, we have made certain assumptions:

1) The material is homogeneous and isotropic;
2) There is no strain before manufacturing;
3) Temperature effect do not consider when manufacturing;
4) It obeys the laws of the Hooke's Law in elastic stage;
5) It obeys the von Mises yield rule and Prandtl-Reuss plastic flow rule;
6) It contains Isotropic strain hardening in constitutive equation;
7) There are elastic strain stage and plastic strain stage in material strain rate;
8) Punch, die and holder are steel structure;
9) The Bauschinger effect does not consider in reverse unloading.

After assuming above, the constitutive relation can be written as follows:

$$\overset{\circ}{\sigma}_{ij} = C^{ep}_{ijmn}\dot{\varepsilon}_{mn}, \tag{2}$$

$$C^{ep}_{ijmn} = C^{e}_{ijmn} - \frac{C^{e}_{ijkl}C^{e}_{uv}\dfrac{\partial f}{\partial\sigma_{kl}}\dfrac{\partial f}{\partial\sigma_{uv}}}{C^{e}_{kluv}\dfrac{\partial f}{\partial\sigma_{kl}}\dfrac{\partial f}{\partial\sigma_{uv}} + H'\dfrac{\sigma_{uv}\dfrac{\partial f}{\partial\sigma_{uv}}}{\bar{\sigma}}}, \tag{3}$$

where $\overset{\circ}{\sigma}_{ij}$ is Jaumann differential of σ_{ij}, C^{ep}_{ijmn} is the elastic-plastic module, C^{e}_{ijmn} is Elastic module, f is the initial yield function, H' is the strain hardening rate, $\bar{\sigma}$ is Von Mises yield function, the Matrix form of C^{ep}_{ijmn} can be expressed as below:

$$\left[C^{ep}\right] = \left[C^{e}\right] - \frac{1}{S}\begin{bmatrix} S_1^2 & S_1S_2 & S_1S_3 & S_1S_4 & S_1S_5 & S_1S_6 \\ & S_2^2 & S_2S_3 & S_2S_4 & S_2S_5 & S_2S_6 \\ & & S_3^2 & S_3S_4 & S_3S_5 & S_3S_6 \\ & & & S_4^2 & S_4S_5 & S_4S_5 \\ & & & & S_5^2 & S_5S_6 \\ symm & & & & & S_6^2 \end{bmatrix}, \tag{4}$$

where,

$$S = \frac{4}{9}\bar{\sigma}^2 H' + S_1\sigma'_{xx} + S_2\sigma'_{yy} + S_3\sigma'_{zz} + 2S_4\sigma'_{yz} + 2S_5\sigma'_{zx} + 2S_6\sigma'_{xy}, \tag{5}$$

$$S_1 = 2G\sigma'_{xx}, S_2 = 2G\sigma'_{yy}\ S_3 = 2G\sigma'_{zz}, \tag{6}$$

$$S_4 = 2G\sigma'_{yz},\ S_5 = 2G\sigma'_{zx},\ S_6 = 2G\sigma'_{xy}, \tag{7}$$

where σ'_{ij} is deviator of σ_{ij}, G is the friction flow potential, $G = \sigma_1^2 + \sigma_2^2$, $\left[C^e\right]$ is the equation in minimum strain, which can be expressed as:

$$\left[C^e\right] = \frac{E}{1+\nu}\begin{bmatrix} \frac{1-\nu}{1-2\nu} & \frac{1-\nu}{1-2\nu} & \frac{1-\nu}{1-2\nu} & 0 & 0 & 0 \\ & \frac{1-\nu}{1-2\nu} & \frac{1-\nu}{1-2\nu} & 0 & 0 & 0 \\ & & \frac{1-\nu}{1-2\nu} & 0 & 0 & 0 \\ & & & \frac{1}{2} & 0 & 0 \\ & & & & \frac{1}{2} & 0 \\ symm & & & & & \frac{1}{2} \end{bmatrix}, \tag{8}$$

where E is modulus of elasticity, v is Poisson's ratio. If the material is homogeneous and isotropic, the elastoplastic rate equation can be written:

$$\overset{\circ}{\sigma}_{ij} = \frac{E}{1+\nu}\left[\delta_{ik}\delta_{jl} + \frac{\nu}{1-2\nu}\delta_{ij}\delta_{kl} - \frac{3\alpha\left(\frac{E}{1+\nu}\right)\sigma'_{ij}\sigma'_{kl}}{2\bar{\sigma}^2\left(\frac{2}{3}H' + \frac{E}{1+\nu}\right)}\right]\dot{\varepsilon}_{kl}. \tag{9}$$

If α=1, it is a plastic stage; when α =0, it is a elastic stage or unloading stage.

Equivalent stress and equivalent plastic strain relations can express by n-power law equation:

$$\dot{\sigma} = C\left(\varepsilon_0 + \dot{\varepsilon}_p\right)^n, \tag{10}$$

where C is material constant, n is strain hardening index; $\dot{\sigma}$ is the equivalent stress, $\dot{\varepsilon}_p$ is the equivalent plastic strain, ε_0 is the initial strain.

2.1.3 The finite element equation

Finite element analysis is the method that the structure is divided into many small units called discrete entity. Based on Large deformation stress and stress rate relation, the finite deformation of update Lagrangian formulation, material constitution relationship, the velocity distribution of each unit is show below:

$$\{v\} = \le [N]\{\dot{d}\}, \tag{11}$$

$$\{\dot{\varepsilon}\} = \le [B]\{\dot{d}\}, \tag{12}$$

$$\{L\} = \le [M]\{\dot{d}\}, \tag{13}$$

where $\left[N\right]$ is shape function, $\left\{\dot{d}\right\}$ is nodal velocity, $\left[B\right]$ is strain rate-velocity matrix, $\left[M\right]$ is velocity gradient-velocity matrix

The principle of virtual work equation and the constitutive equation based on update Lagrangian are linear equation. The formula can be written by the form of incremental representation.

After finite element discretization, the large deformation rigid general equation is written as below:

$$\left[K\right]\left\{\Delta u\right\}=\left\{\Delta F\right\}, \tag{14}$$

where:

$$\left[K\right]=\sum_{\langle E\rangle}\int_{V^e}\left[B\right]^T\left(\left[C^{ep}\right]-\left[Q\right]\right)\left[B\right]dV+\sum_{\langle E\rangle}\int_{V^e}\left[E\right]^T\left[Z\right]\left[E\right]dV, \tag{15}$$

$$\left\{\Delta F\right\}=\sum_{\langle E\rangle}\int_{S^E}\left[N\right]^T\left\{\dot{f}\right\}dS\Delta t, \tag{16}$$

where $\left[K\right]$ is the overall elastoplastic stiffness matrix; $\left\{\Delta F\right\}$ is the nodal displacement increment; $\left\{\Delta u\right\}$ is the nodal forces incremental; $[Q]$ and $[Z]$ are stress correction matrix.

2.1.4 Friction processing

There is friction in sheet forming process, so we need to pay attention to materials and tools of the interface conditions. When the material moves along the tool surface curve of the slide, the contact force can be expressed as:

$$F=F_l l+F_n n, \tag{17}$$

where F_l is radial force and F_n is normal force, and differential equation of F can be expressed as:

$$\dot{F}=\dot{F}_l l+F_l\dot{l}+\dot{F}_n n+F_n\dot{n}, \tag{18}$$

where differentials of $\dot{l}$ and $\dot{n}$ are expressed as:

$$\dot{l}=-\Delta u_l^{rel}/R, \tag{19}$$

$$\dot{n}=\Delta u_l^{rel}/R, \tag{20}$$

where R is tool radius, Δu_l^{rel} is the local relative velocity between the tool and node, and the nodes relative speed can be expressed as:

$$\Delta u_l^{rel}=\Delta u_l-\dot{u}_{tool}\sin\theta, \tag{21}$$

where Δu_l is the contact tangent displacement increment of nodes, $\dot{u}_{tool}$ is the displacement increment of tooling, θ is the rotation angle.

The increment equation of $\dot{F}$ is expressed as follow:

$$\dot{F}=\left(\dot{F}_l-F_n\Delta u_l/R+F_n\dot{u}_{tool}\sin\theta/R\right)\cdot l+\left(\dot{F}_n-F_l\Delta u_l/R-F_l\dot{u}_{tool}\sin\theta/R\right)\cdot n. \tag{22}$$

Rigid matrix governing equation of the contact nodes is expressed below:

$$\begin{bmatrix}K & \cdots & \cdots\\ \cdots & K_{11}+F_n/R & K_{12}\\ \cdots & K_{21}+F_n/R & K_{22}\end{bmatrix}\cdot\begin{Bmatrix}\cdots\\ \Delta u_l\\ \Delta u_n\end{Bmatrix}=\begin{Bmatrix}\cdots\\ \dot{F}_l+F_n\dot{u}_{tool}\sin\theta/R\\ \dot{F}_l-F_l\dot{u}_{tool}\sin\theta/R\end{Bmatrix}. \tag{23}$$

2.1.5 Incremental steps of R_{min} method

Based on the elastic plastic finite element method with large deformation method, the Yamada r_{min} method [9] is used to judge the function. Each incremental step value is equal to incremental displacement of initial deformation increment of the tooling. Adopted the method of updated Lagrangian formulation, calculated each increment of displacement, strain, stress, load, spring-back value after forming the final shape of sheet mental in unloading condition, the value of load incremental in each step is controlled by $r_{\min}$ method, which is shown as below:

$$r_{\min}=MIN(r_1,r_2,r_3,r_4,r_5), \tag{24}$$

where, r_1 is the maximum allowable strain increment, r_2 is the maximum allowable rotation increment, r_3 is the minimum value in all elastic elements, r_4 is the contact position between free node and tooling, r_5 is the discontent position between free node and tooling.

2.2 NUMERICAL ANALYSIS

2.2.1 *Numerical analysis flow*

Based on the finite deformation theory, ULF equation and $r_{\min}$ method, a set of effective analysis of sheet metal forming process is established. Firstly, a 3D part and mold is designed with the NX software, and then is meshed with NASTRAN software. Secondly, the meshed model is drawn into the data file and did finite element analysis. The simulation flow chart is shown in Figure 1.

Based on the theory upwards, the bending process of U plate type is studied, including relationship between the punch load and displacements, stress and strain, thickness, spring-back and warpage. Some simulation experiments were carried out, of which parameters are friction coefficient (μ), punch radius (r_p), die radius (R_d). The results were verified by the experiment, and optimized and served a reference for U bending designer.

The whole experimental structure is composed of punch, die and blank holder. The experimental model picture was shown as Figure 2 below.

The initial relation of part and die is shown in Figure 2a, also, the punch down a certain stroke is shown Figure

2b. It takes two coordinates to solve the problem, which are fixed coordinates (X, Y, Z) and local coordinates (ξ, η, ζ). based on the right-hand rule, it uses the fixed coordinates (X, Y, Z) when nodes do not contact with the tool, and uses the local coordinates (ξ, η, ζ) when nodes contact with the tool. L-axis is the tangential direction of contact line between the part and tools when n-axis is the normal direction.

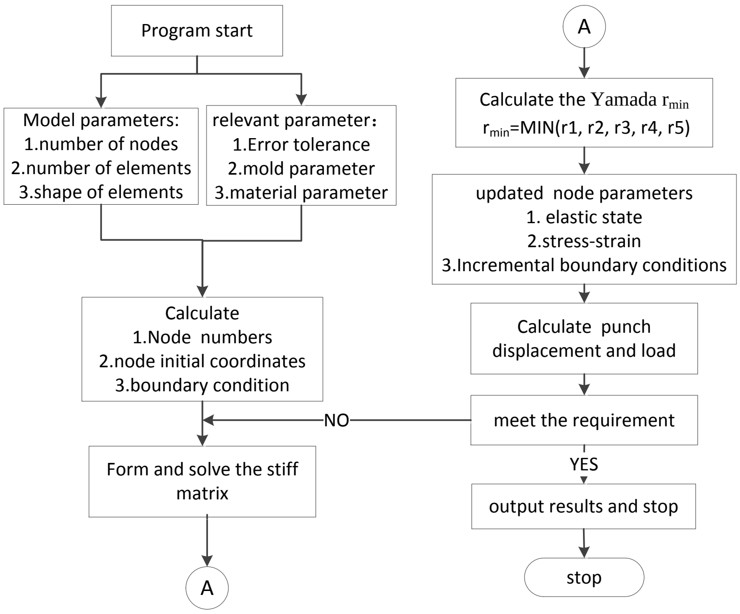
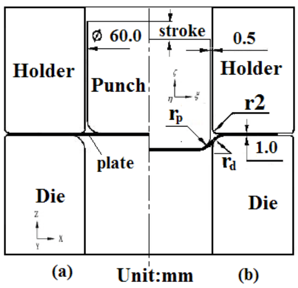


FIGURE 1 Numerical simulation of flow chart



a) before deformation, b) after deformation
FIGURE 2 Sheet metal and die size chart

The contact condition of each node of plates will change which based on deformation in sheet metal forming. When the displacement increment is zero, the boundary conditions of increment displacement of the next node will changes to free node boundary conditions. After checking the contact condition between the part and tool, generalized Rmin method is used. if sheet contacts the mold, the boundary condition will be changed to the contact condition.

Because the structure of sheet model is symmetrical, we take the 1/4 model to analysis.

It uses the quadrilateral segmentation of degenerated shell element in sheet metal meshing, when the die meshing uses the triangle segmentation.

Material parameters for numerical simulation are shown in Table 1 below, the shape of part is rectangular, Length L=120mm, Width W=50mm.

TABLE 1 Material property parameters.

Thickness	T=1mm
Length	L=120mm
Width	W=50mm
Yield stress	σ_y=131MPa
Young's modulus	E=210000MPa
Poisson's ratio	ν=0.3
Friction factor	μ=0.14

3 Results and discussion

3.1 STRESS DISTRIBUTION ANALYSIS

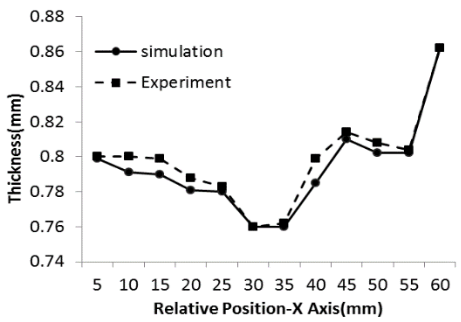
As can be seen from the result of simulation in Fig. 3, the initial stress mainly concentrates in fillet of die and punch. When the stroke is 12mm, the mainly stress concentrates in the area of punch fillet, some stress slightly and warpage occurs in bottom. The stress gradually shifted to the side wall plate with the increasing of stroke. When the stroke is 35mm, the sheet detaches the holder, the warping stress eliminates gradually, but the wall tress also exists.

3.2 THICKNESS ANALYSIS

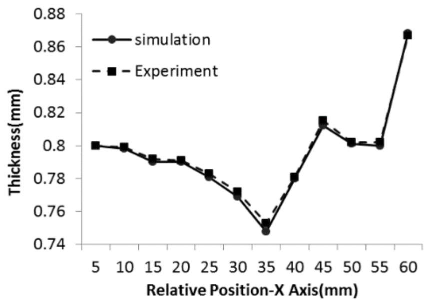
After pressing, there is different stress in U-bending process of the sheet mental. Thickness would be chicken and thinning. In order to study the changes regulation between the thickness and fillet radius of die and punch, four simulation experiments are arranged, such us: r_p=4mm, r_p=8mm, R_d=4mm, R_d=8mm. The thickness of sheet in different position of the X-Axis are measured and recorded in Table 2 below.

TABLE 2 The thickness of sheet in different Relative position-X Axis under different parameters

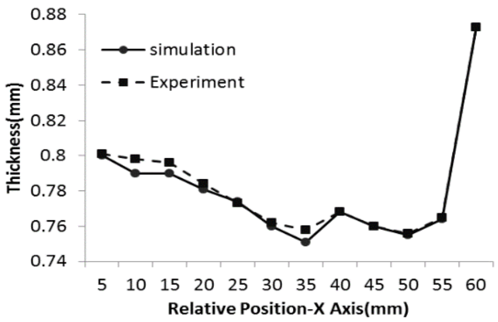
Parameters	Simulation	Experiment	Simulation	Experiment	Simulation	Experiment	Simulation	Experiment
Relative position – X-Axis(mm)	r_p=4mm		r_p=8mm		R_d=4mm		R_d=8mm	
5	0.799	0.800	0.800	0.800	0.800	0.801	0.800	0.801
10	0.791	0.800	0.798	0.799	0.790	0.798	0.800	0.800
15	0.790	0.799	0.790	0.792	0.790	0.796	0.790	0.798
20	0.781	0788	0.790	0.791	0.781	0.784	0.781	0.786
25	0.780	0.783	0.781	0.783	0.774	0.773	0.770	0.775
30	0.760	0.760	0.769	0.772	0.760	0.762	0.768	0.768
35	0.760	0.762	0.748	0.753	0.751	0.758	0.751	0.756
40	0.785	0.799	0.780	0.781	0.768	0.768	0.783	0.785
45	0.810	0.814	0.812	0.815	0.760	0.760	0.812	0.814
50	0.802	0.808	0.801	0.802	0.755	0.756	0.801	0.802
55	0.802	0.804	0.800	0.802	0.764	0.765	0.800	0.801
60	0.862	0.862	0.868	0.867	0.873	0.873	0.862	0.863



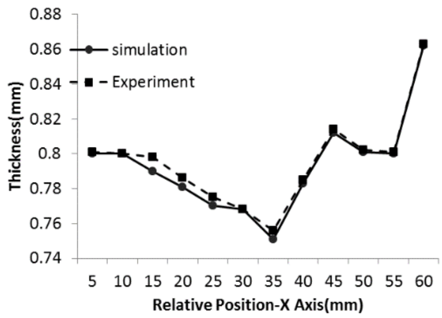
a) r_p=4mm



b) r_p=8mm



c) R_d=4mm



d) R_d=8mm

FIGURE 4 Thickness distribution chart under different parameters

As can be seen from the Figure 4, Thickness distribution of sheet can be divided into three regions. The relative positions are from the 0mm to 20mm; the sheet contacts to the punch closely; the thickness is no obvious change. The second area is from the 20mm to 40mm, the sheet is under the axial stress in the area of die fillet, and thin gradually. The third area is from the 40mm to 60mm, the sheet is squeezed into die accompany with punch movement; the sheet flow is hindered, and the thickness increase.

3.3 WARPAGE AND SPRING-BACK ANALYSIS

The reason of warpage in U-Bending is that the sheet which affected by die constraint effect moves along the die side wall, when the punch moves down and sheet slips into the die. The outside edge of sheet is continuous, and reverse force is generated in curve bend, and forces the sheet to deform and warp at bottom of punch.
Measurement method of warpage and springback is shown as Figure 5.

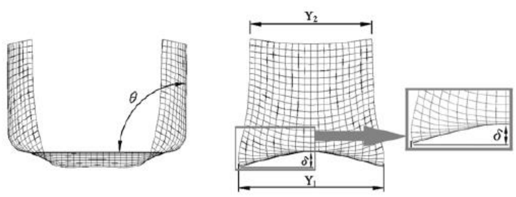


FIGURE 5 Measurement location of warpage and the Springback angle

As can be seen from the Figure 6, the relationship is shown between the relative position and warpage with the different punch stroke. When the stroke is 12.0mm, the warpage is 2.13mm. When the stroke is 16.0mm, the warpage is 3.62mm. When the stroke is 40.0mm, the warpage is 4.72mm. When unload; the warpage is 4.71mm. The warpage mainly form when the stroke is from 0mm to12.0mm, and it changes slowly outside that scope.

In order to study the change law between warpage and fillet radius of different punch and die, improve the quality of sheet, the simulation experiments, which follow the arrangement below are carried out. Firstly, the punch fillet radius is fixed 6mm, die fillet radius are change from 2mm, 4mm, 6mm, 8mm to 10mm. Secondly, the die fillet radius is fixed 6mm, punch fillet radius are change from 2mm, 4mm, 6mm, 8mm to 10mm. the simulation and experiment results are recorded in Tab3.

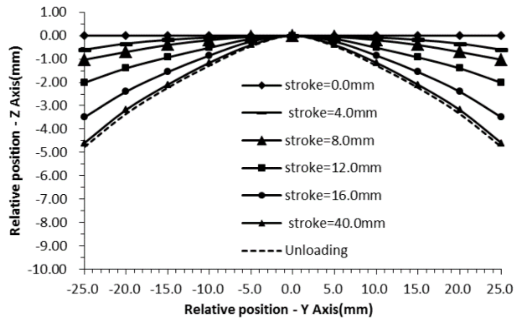


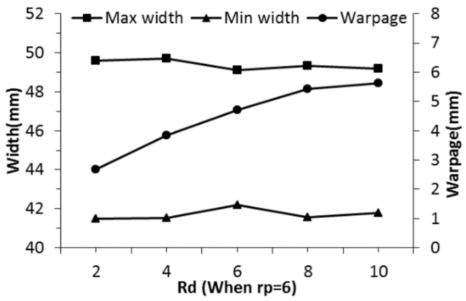
FIGURE.6 The relationship between the relative position and warpage with the different punch stroke

TABLE 3 Analysis results of warpage and angle in different parameters

Parameters r_p	R_d		Warpage (mm)	Angle (°)	Max width (mm)	Min width (mm)
6.0	2.0	Sim.	2.67	90.1°	49.6	41.48
		Exp.	2.68	90.1°	49.56	41.53
	4.0	Sim.	3.85	90.1°	49.72	41.52
		Exp.	3.82	90.5°	49.38	41.63
	6.0	Sim.	4.72	90.1°	49.12	42.21
		Exp.	4.87	91.3°	48.92	42.82
	8.0	Sim.	5.42	90.5°	49.32	41.57
		Exp.	4.96	91.1°	49.03	41.75
	10.0	Sim.	5.63	90.1°	49.17	41.78
		Exp.	5.69	90.8°	49.34	42.03
2.0	6.0	Sim.	5.81	90.2°	49.36	42.32
		Exp.	6.52	91.5°	49.42	42.81
4.0		Sim.	5.24	92.3°	49.03	42.21
		Exp.	5.81	91.5°	48.92	42.81
6.0		Sim.	4.72	90.1°	49.12	42.21
		Exp.	4.87	91.3°	48.92	42.82
8.0		Sim.	4.08	90.1°	49.72	42.03
		Exp.	3.85	90.1°	49.65	42.62
10.0		Sim.	3.54	90.6°	49.87	41.32
		Exp.	3.50	90.2°	49.82	41.43

Note: sim.: simulation value, exp.: experiment value, r_p: Punch radius, R_d: Punch radius.
Sheet size: L=120.0mm, W=50.0mm.

As can be seen from the Figure 7, the experimental and simulation results are basically similar. When the punch radius is unchanged, die radius is smaller and warpage is smaller. When the die radius is unchanged, punch radius is smaller but warpage is greater. The best warpage is appear when punch radius r_p=6mm, die radius R_d=2mm, the Min value is 2.67, the changes of Spring-back and width are relatively small.



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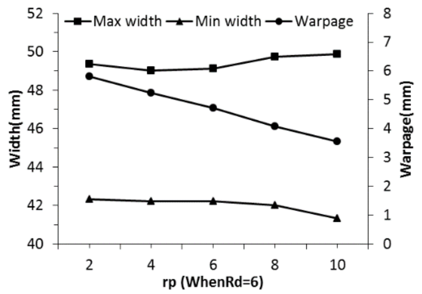

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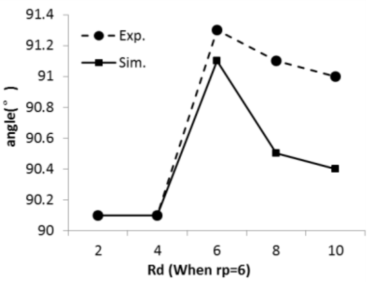

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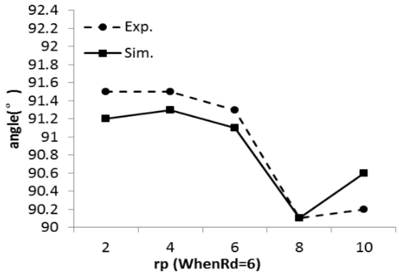

d)

FIGURE 7 Warpage and spring back angle distribution chart under different parameters

4 Conclusion

Based on the numerical analysis and experimental results, combined with finite element method with the incremental elasto-plastic theory, analysed warpage phenomenon in U-bending process of sheet metal, the following conclusions are obtained as follows.

1) The maximum stress is mainly concentrated in the fillet of punch and die. With the stroke's moving, the stress shifts to the side wall and the distribution is quite uniform.

2) From simulation results it is shown the thinnest of sheet occurs at the fillet of punch, and if rupture, the position will be here. In addition, the end piece of long-axis occurs the thickening.

3) From simulation results it is shown the warpage occurs at tangent of punch and die fillet. Maximum warping appears when the stroke is from 0mm to 12.0mm.When the punch radius is constant, the die radius is smaller, the warpage is smaller too, Figure 7a. When the die radius is constant, the punch radius is greater, but the warpage is smaller, Figure 7b.

For additional experiments analysis, the min warpage can be predicted that when punch radius is 10.0mm, the die radius is 2.0mm, and the warpage can reduce to the minimum 2.52mm. These results are applied to engineering.

Acknowledgment

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