Microforming analysis of 304 stainless steel with several grains across the section

Ying Zhang [1, a] , Chenyu Xie [1, b], Zhengjun Yuan [1, c]

[1] School of Mechanical and Electrical Engineering, Shandong Jianzhu University, Jinan 250101, China；

[a] zhangying@sdjzu.edu.cn, [b] xiechenyu@sdjzu.edu.cn , [c] yuanzhengjun@sdjzu.edu.cn

Abstract. Thickness of the metal material reaches micron level, its mechanical properties show a certain size effect. The cupping test can evaluate the forming performance of thin metal sheet. In this paper, ultra-thin 304 stainless steel with the thicknesses of 0.03 mm, 0.06 mm and 0.1 mm is selected as the test materials. The forming performance is studied through test. Simulation analysis is also established to investigate the influence of parameters on the forming performance.

Keywords：Steel; Microforming;Manufacturing; Simulation; Grain size.

1. Introduction

With the progress and development of science and technology, metal materials are more and more widely used in some precision instruments. When the thickness of the metal material reaches micron level, its mechanical properties show a certain size effect.

The uniaxial tensile test and flanging test of Engel indicate that smaller the size, smaller the flow stress[1]. Kals found the behavior for CuNi18Zn20 that with miniaturizing the specimen dimensions both in the tensile test and air bending test, the flow sress decreases[2]. Raulea carried out tensile and blanking experiments on thin aluminum plates, and found that when the grain size is constant, the yield strength decreases with the thinning of the plate thickness[3]. Geiger found in the micro-tensile and micro-pier coarse tests of brass, pure aluminum, copper and other materials that the material showed the size effect of “smaller and weaker” in the micro-plastic deformation process[4]. Many researchers have summarized some rules through analysis of the sheet forming technology[5-9]. Both the experiment and the numerical simulations show a significant influence of the size effect at the sheet microforming[10] .It is clear that the flow stress decreases with reduction of specimen size and increase of grain size[11]. Fracture strain decreases with the decrease of workpiece size and increase of grain size in tensile tests of sheet metal and wire[12-13].

In this paper, ultra-thin 304 stainless steel with the thicknesses of 0.03 mm, 0.06 mm and 0.1 mm is selected as the test materials. Firstly, the stress and deformation under tensile and plane tensile conditions are compared through tensile test and cupping test. Then, through the simulation analysis of cupping test, the influence of friction coefficient, the thickness anisotropy coefficient and blank holder force on the forming performance is mainly studied.

2. Experiment

2.1 Tensile test

The composition of stainless steel 304 is shown in Table 1. The test specimens are made according to the rolling directions of 0°, 45° and 90° of the sheet metal, and the specimen sizes are shown in Fig.1. Uniaxial tensile tests are carried out on CMT5105 microcomputer controlled electronic universal testing machine. The mechanical properties of 304 stainless steel foils with three different thicknesses are measured. The tensile mechanical curves are shown in Fig.2 .

Table.1 304 Chemical composition of stainless steel (WT %)

Part	C	Si	Mn	P	S	Cr	Ni
content	0.07	0.32	1.06	0.029	0.003	18.01	8.05

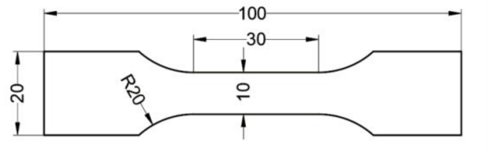
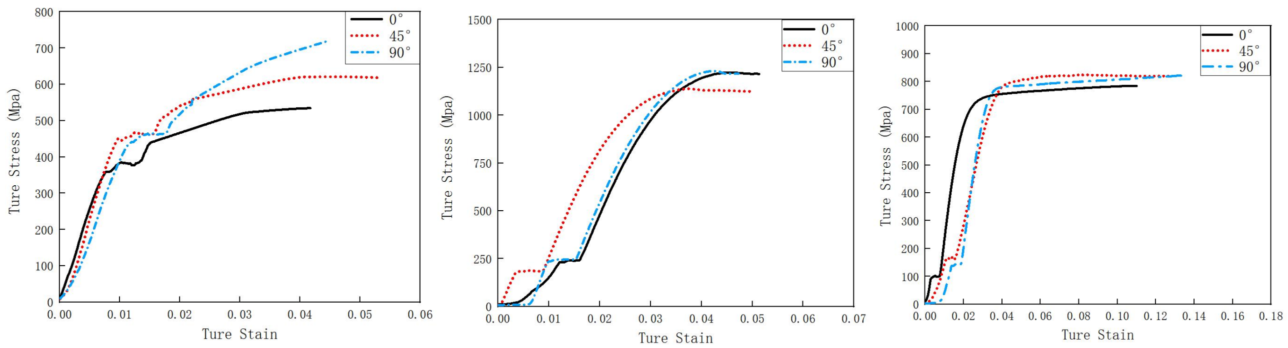


Fig.1 Size and geometry of tensile specimen (mm)



(1) Thickness of 0.03mm (2)Thickness of 0.06mm (3) Thickness of 0.1mm

Fig.2 Stress - strain curve

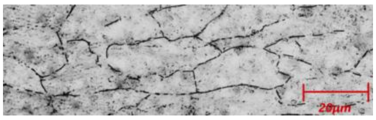
According to the mechanical curve, the average value of the material anisotropy is calculated. The bilinear elastic-plastic model is used in the constitutive model. The tangent modulus is fitted by the least square method for the linear change of material in plastic stage. The thickness anisotropy coefficient of three different directions corresponding to the rolling direction is also different, taking three average values, such as Formula 1.

$$\bar{r} = \frac{r_0 + r_{90°} + 2r_{45°}}{4} \quad (1)$$

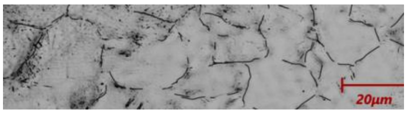
As shown in Table 2, the yield stress of the specimen with 0.03 mm thickness is largest, but the tensile stress, the thickness anisotropy coefficient and failure strain are smallest. The tensile stress of the specimen with 0.06 mm thickness is the largest, and the thickness anisotropy coefficient is also larger, indicating that it is not easy to deform in the thickness direction of the material and has better forming performance. The failure strain of specimens with 0.1 mm thickness is the largest, which indicates that larger deformation can be achieved under tensile condition. The grain distribution on the transverse surface of metal foil is observed through metallographic test in Fig.3. The average grain size of three kind thickness specimen is about 20-30μm. The grain shape of 0.03mm thickness specimen is more narrow. The ratio of specimen thickness to grain size affected the mechanical properties of the material.

Table.2 Performance Parameters of Materials with Different Thickness

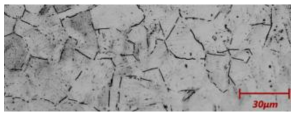
Thickness (mm)	Yield stress （MPa）	Tensile strength （MPa）	Failure strain	Thickness anisotropy coefficient	Elastic modulus （GPa）	Tangent modulus （GPa）
0.03	431	622	0.0507	1.02	205	4.5
0.06	222	1188	0.054	1.62	205	5.9
0.1	133	700	0.13	1.25	205	2.6



（1） Thickness of 0.03mm



（2）Thickness of 0.06mm



（3）Thickness of 0.1mm

Fig.3 304 stainless steel grains

2.2 Cupping test

The cupping test principle is shown in Fig.4, including punch, blank holder and die. The punch makes the specimen plastically deformed, and the diameter d is 20 mm. The die can form the required shape of the specimen, with the inner hole diameter of 22.2 mm and the die fillet R of 1 mm. The blank holder is used to press the specimen to prevent the specimen from wrinkling. The cup-burst mould is shown in Fig.5, in which the guide pillar and the guide pillar fixing device are used for positioning to ensure the neutrality of the punch downward process. The cup test is carried out on the CMT5105 universal testing machine (Fig.6). The forming speed is 1 mm/min. The forming force curve is shown in Fig.7, and the maximum curve is the fracture point. In the initial stage, the deformation force of specimen with 0.06 mm thickness is the largest, but the IE value of 0.1 mm thickness reached the largest. Compared with the mechanical indexes of tensile test, the specimen with 0.06 mm thickness has the largest deformation force both in uniaxial loading test and the cup protrusion test. The tensile failure strain of 0.1 mm thickness specimen is the largest, and the IE value is also the largest in the cupping test. No matter tensile test and cupping test, the deformation force and cupping value IE of 0.03 mm thickness specimen are the smallest.

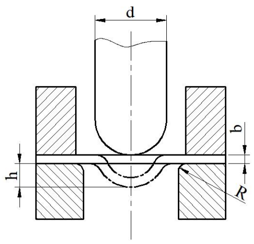


Fig. 4 Principle of cupping test

Fig. 5 Cup test device


Fig. 6 Tensile testing machine

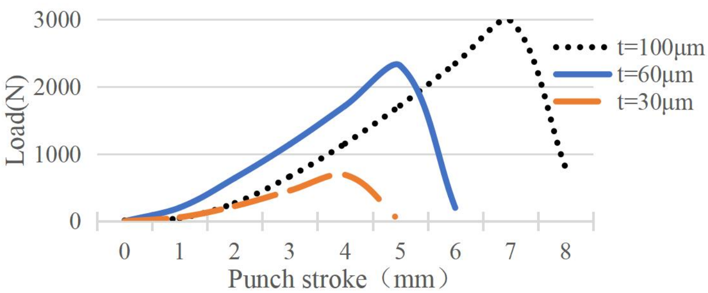


Fig.7 Forming force

The wire cutting equipment is used to cut the specimen formed by cupping along the diameter. Four positions are taken from the inside to the outside along the radius of the specimen, namely, the center of the specimen, the 1/4 position of the specimen radius, the corner and the blank holder position of the specimen. The thickness of the specimen at four locations is measured. The test process is shown in Fig.8 and the thickness is shown in Table 3. The thickness of the specimen decreases from the center to the outside, and the thinning at the center is the most obvious. The central thinning rate of 0.06 mm thickness specimen is slightly greater than that of 0.1 mm thickness specimen.

Table 3 Test thickness (mm)

Number	Position	0.06 mm thickness specimen	0.1 mm thickness specimen
1	Center	0.050	0.078
2	1/4	0.055	0.089
3	Fillet	0.058	0.099
4	Edge roll	0.060	0.100

3. Finite element simulation analysis

Using LS-DYNA finite element software to simulate the cup process, the process of material flow and crack generation in the forming process can be analyzed, and the data difficult to detect in the test can be obtained.

3.1 Preliminary treatment

The finite element simulation model is established as shown in Fig.9, and the cup specimen is simplified as punch, blank holder, die and specimen. Through repeated comparison, it is most reasonable to divide the specimen model grid into 0.2 mm.

In the material model setting, the punch, blank holder and die are set as rigid bodies. The transverse anisotropic hardening model is used for 304 stainless steel foil, and the shell element is selected. The mechanical properties of the material model are input into the data obtained from the tensile test.The simulation model includes three pairs of contacts, namely, the contact between punch and specimen, the contact between blank holder and specimen, and the contact between die and specimen. The three pairs of contacts are set as automatic surface-surface contact. According to the test of contact surface lubrication using PTFE and vaseline, friction coefficient is set to 0.1.

By calculating the bolt preload, it is concluded that the blank holder force F is 1.2 kN. The movement is set as that the die is fixed, and the punch, blank holder and specimen are allowed to move in the forming direction of the specimen. The punch is set to move at a constant speed of 1.0 mm/min, and the speed and blank holder force are applied to the punch and blank holder circle respectively by curve definition (Fig.10).

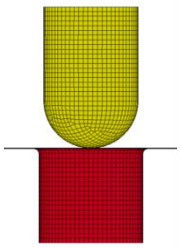


Fig. 9 Simulation model

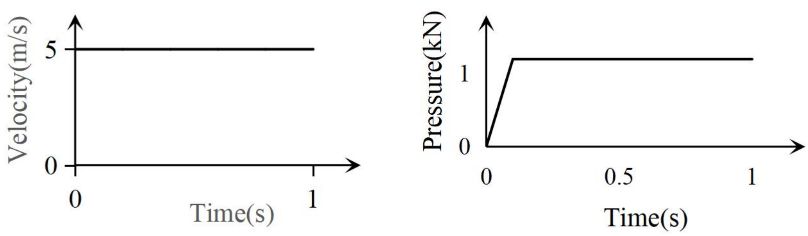
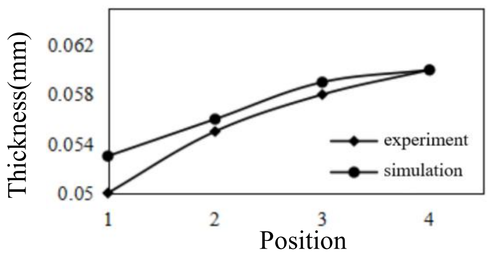


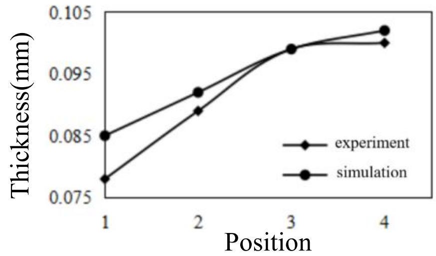
Fig. 10 Loading curve

3.2 Result analysis

The thickness of the simulated specimen is compared with that of the specimen at four positions measured by the cupping test, as shown in Fig.11. The thickness distribution of the simulation results is consistent with that of the test results, and the fracture position of the specimen occurs in the maximum area of the simulation thickness reduction during the test, so the simulation results are reasonable.



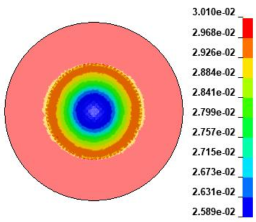
（1）Thickness of 0.06mm



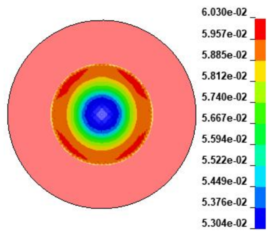
（2）Thickness of 0.1mm

Fig. 11 Thickness comparison between test and simulation

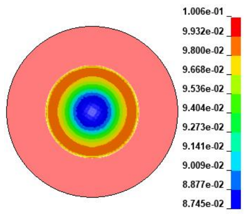
When the three thickness specimens reach a certain cup protrusion depth, the thickness distribution nephogram is shown in Fig.12. The thinnest and the largest thinning rate of the three thickness specimens are all located at the center of the specimen. The concave die fillet position is thinner than the nearby position, because the fillet is close to the position pressed by the edge ring, and the fluidity of the metal material is limited and it is easier to get thinner.



（1）Thickness of 0.03mm



（2）Thickness of 0.06mm



（3）Thickness of 0.1mm

Fig. 12 Simulation thickness nephogram

The effects of friction coefficient μ, the thickness anisotropy coefficient and blank holder force on the cup forming of 304 stainless steel metal foil are analyzed by the above simulation results.

3.2.1 Effect of friction coefficient on formability

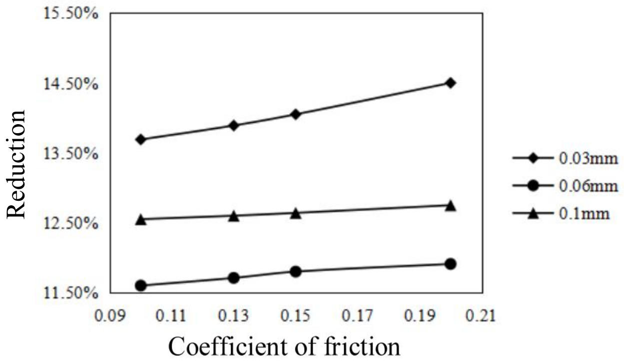
The control variable method is used to ensure that the coefficient thickness anisotropy is 1.1, and the blank holder force is 1.2 kN and other material parameters are unchanged. The influence of the friction coefficient between the punch and the specimen on the maximum thinning rate of 304 stainless steel metal foil is analyzed. When the three specimens with different thicknesses reach the same cupping depth, the maximum thinning rate is shown in Fig. 13. With the increase of friction coefficient, the thinning rates of the three specimens increase. The greater the thinning rate of the 0.03 mm specimen is, the more prone to fracture.

3.2.2 Effect of the thickness anisotropy coefficient on forming performance

The influence of the thickness anisotropy coefficient on material thickness is analyzed. The friction coefficient is set to 0.1, and the blank holder force is set to 1.2 kN. Other parameters remained unchanged. The thickness thinning rates of three thickness specimens at the same cupping depth are shown in Fig. 14. With the increase of the thickness anisotropy coefficient, the thinning rate of the specimen get smaller, indicating that the specimen is more difficult to become thinner and rupture.

3.2.3 Effect of blank holder force on forming performance

Control other parameters unchanged, the the thickness anisotropy coefficient is 1.1, friction coefficient is 0.1, analyze the influence of blank holder force on its forming. Similarly, the specimen with three thicknesses reached the same cupping depth, and the comparison of thinning rates is shown in Fig.15. With the increase of blank holder force within a certain range, the thinning rate of the specimen is continuously increased. This is because the greater the blank holder force is, the worse the material flow is, the greater the force that hinders the plastic deformation of the material is, and the material is difficult to flow to the center of the specimen, resulting in the thinner specimen thickness direction with the greater blank holder force at the same cupping depth. But if the blank holder force is too small, the specimen forming process will appear wrinkle phenomenon.



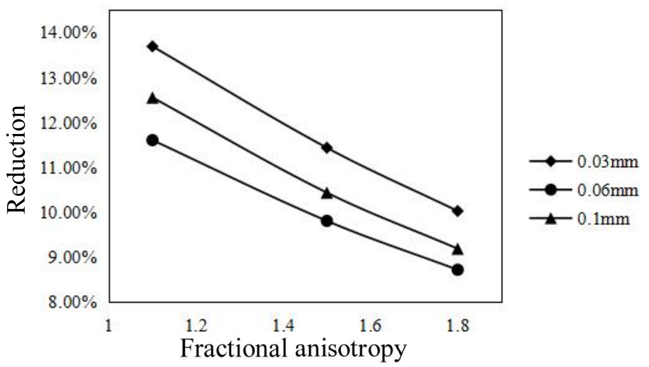


Fig. 13 Effect of friction coefficient Fig. 14 Influence of the coefficient thickness anisotropy

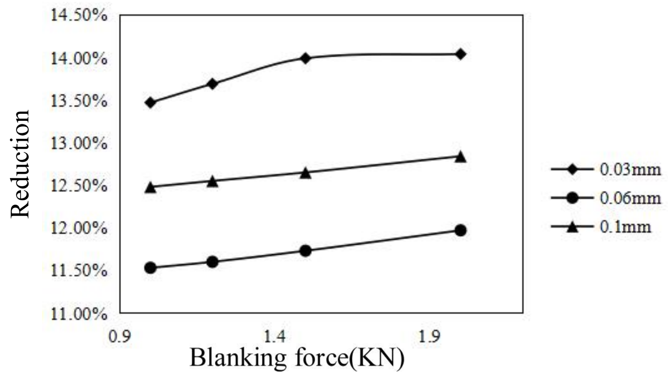


Fig. 15 Effect of blank holder force on thinning rate in a certain range

4. Conclusion

In this paper, ultra-thin 304 stainless steel with the thicknesses of 0.03 mm, 0.06 mm and 0.1 mm is selected as the test material. Firstly, the forming of the material under single tensile and plane stress conditions is compared by tensile test and cupping test, and the cupping test is analyzed by finite element simulation using LS-DYNA software. The conclusions are summarized as follows :

(1)The results of single tensile test and cupping test of three kinds of thickness specimens are similar. The forming force of 0.06 mm thickness specimen is the largest, the forming ability of 0.1 mm thickness specimen is the largest, and the forming force and forming ability of 0.03 mm thickness specimen are the smallest.

(2)Taking the thinning rate as the evaluation index, for the same thickness of 304 stainless steel metal foil, the smaller value of the friction coefficient, the maximum thinning rate is smaller. The higher value of the thickness anisotropy coefficient, the maximum thinning rate is smaller. Under the condition that the pressed specimen does not wrinkle, the smaller value of the blank holder force, the maximum thinning rate is smaller.

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