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Experimental and finite element optimization analysis on hydroforming process of rupture disc

Xiangwei Kong[a, b,]*, Jiancong Zhang[c], Xuqing Li[a,b], Zhibo Jin[a, b], Hai Zhong[a, b], Yu Zhan[a], Fengjuan Han[d]

[a]*School of Mechanical Engineering and Automation, Northeastern University, Shenyang 110819, China*
[b]*Key Laboratory of Vibration and Control of Aero-Propulsion System Ministry of Education, Northeastern University, Shenyang 110819, China*
[c]*Capital Aerospace Machinery Company, Beijing 100076, China*
[d]*ShenyangAerospace Xinguang Safety System Co. Ltd, Shenyang, 110000,China*

Abstract

Rupture disc has been one of the most effective equipment to prevent overpressure from explosion for the pressure equipment. The performance of bursting at the predetermined pressure is critical to rupture disc, which was decided directly with the dimensional accuracy of the rupture disc such as thickness, radius value and arch height. In this paper, a hydroforming FEA rupture disc model was established and factors that affect the dimensional accuracy of the rupture disc, which is friction coefficient, loading rate and value of hydraulic pressure, were discussed. It was found that a better rupture disc dimension accuracy can be obtained by changing the friction condition and loading rate. Based on the real hydroforming process, experiment was carried out and FEA results agreed well with experimental process result. Thus, dimensional accuracy of the rupture disc can be ensured through finite element analysis.

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Keywords: Rupture disc; FEA; Optimization; Thinning ratio; Arch height; Thickness;

* Corresponding author. Tel.: +86-138-4027-0169; fax: +86(0)24-8368-7614.
E-mail address: xwkong@me.neu.edu.cn

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1. Introduction

Rupture disc is widely used in petrochemical industry, aerospace field and energy resource industry as safety device. As a pressure relief device, it will rupture in the set pressure and release the hydraulic pressure or air pressure of the vessel to protect other equipment. The performance of bursting at the predetermined pressure is critical to rupture disc. Otherwise there will be potential dangerous situation such as Liquid leakage. And this performance was related directly with the thickness, radius value and arch height. [1]. So the dimensional accuracy of the rupture disc is very important.

Many researchers focused on the relationship between the rupture disc's dimension and the value of the limit burst pressure. Through a series of tests on the bursting pressure of rupture disc, Malakhov et al. [2] gave out the experimental coefficient values which make it possible to guarantee that rupture disc fail within a pressure range. Stepanov [3] shows the importance of rupture disc's thickness to rupture pressure reproducibility. Miller [4] reviewed some actual practices and preventative measures that can improve rupture disc performance and stabilize the limit rupture pressure. Gao et al. [5] gave a formula to predict the limit burst pressure value of forward rupture disc and factors like the pole of bulge profile and tensile instability were considered. It was found that the strain-hardening exponent didn't influence the limit burst pressure which is in direct proportion to the strength coefficient of sheet metal. Lee et al. defined their manufacturing design range of cross-scored rupture disc based on the result of Finite Element Analyses. The predicted rupture disc's limit burst pressure value and grooving depth for each thin-plate thickness agreed well with the experimental result [6, 7]. Yan [8] build a Finite Element model to evaluate the effect of the shape and length of cross-scored forward rupture to the value of limit burst pressure. But few of them had studied what factors will affect the dimensional accuracy of the rupture disc.

The purpose of this paper is to study the effect of factors in the process of hydroforming Processes like friction coefficient, loading rate and value of hydraulic pressure, to the dimensional accuracy of the rupture disc which includes the value of arch height and top part's thinning ratio of the burst disc. During the plastic deformation of the rupture disc, a number of different values of friction coefficient and hydraulic pressure were discussed through Finite Element model. Based on linear loading method, the relationship between the different loading rate, arch height and top part's thinning ratio was discussed [9]. Finite element analysis (FEA) was carried out by software ABAQUS and the analysis result agreed well with experimental process result.

2. Finite element model

2.1. FEA modeling

In this paper, the rupture disc is made by 316L stainless steel through hydroforming. Hydroforming uses the von Mises yield criteria coupled with an isotropic work hardening assumption. Young's modulus is 196 GPa and Poisson's ratio is 0.3. The material property used in the finite element analysis is the real stress-strain curve of 316L which was acquired by standard biaxial tensile test and experimental result is shown in Fig. 1.

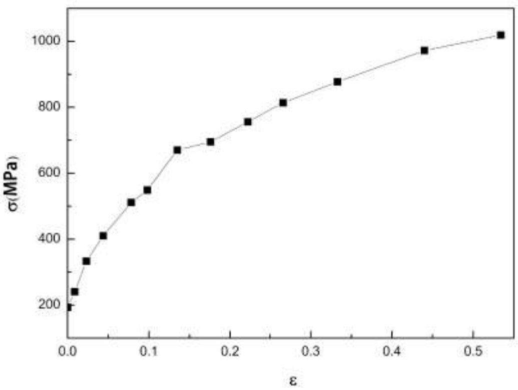

Fig. 1. Real stress-strain curve of 316L.

Figs. 2 and 3 are the geometry of the rupture disc and holding device of the rupture disc. Parameter *D* and *d* are the external diameter and inner diameter of the rupture disc. *S* is the initial thickness of the 316L sheet before hydroforming. *S* = 1 mm. S_1 is the thickness of the top part after hydroforming. *η* is the top part thinning ratio of the rupture disc and $\eta=(S-S_1)/S$. *P* is the water pressure. According to the design requirement of the actual working condition, arch height range value is between 4.5 mm to 6 mm. However, top part of the holding device's dimension: *L*=10mm, which means this is a free bulging process and have no friction between the rupture disc and mold. But the friction between the holding device and rupture disc can't be neglected.

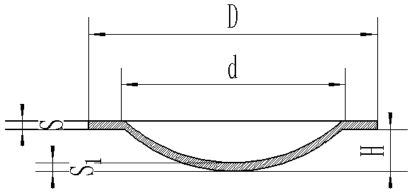

Fig. 2. Geometry of rupture disc.

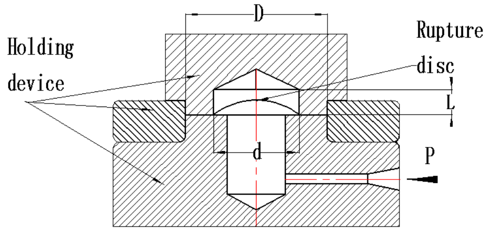

Fig. 3. Holding device and forming status.

The finite element type of the rupture disc during the hydroforming process is based on the C3D8R of ABAQUS. Solving method is general static. The models are shown in Fig. 4. Load method is shown in Fig. 4(d). Water pressure distributes uniformly.

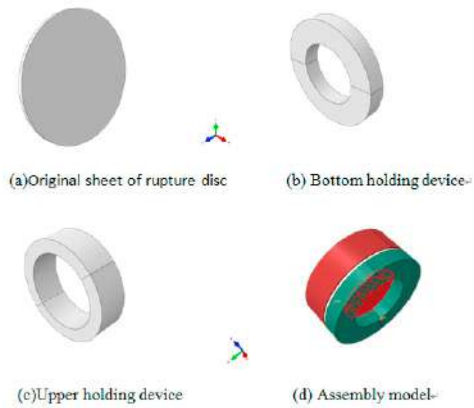

Fig. 4. Finite element model of rupture disc.

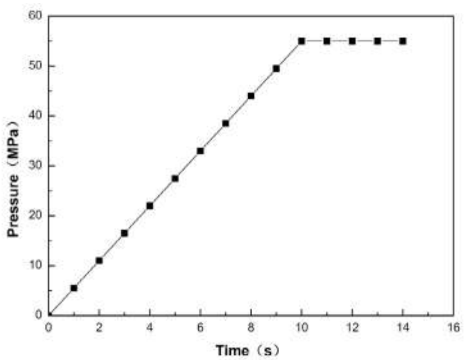

Fig. 5. Real loading rate.

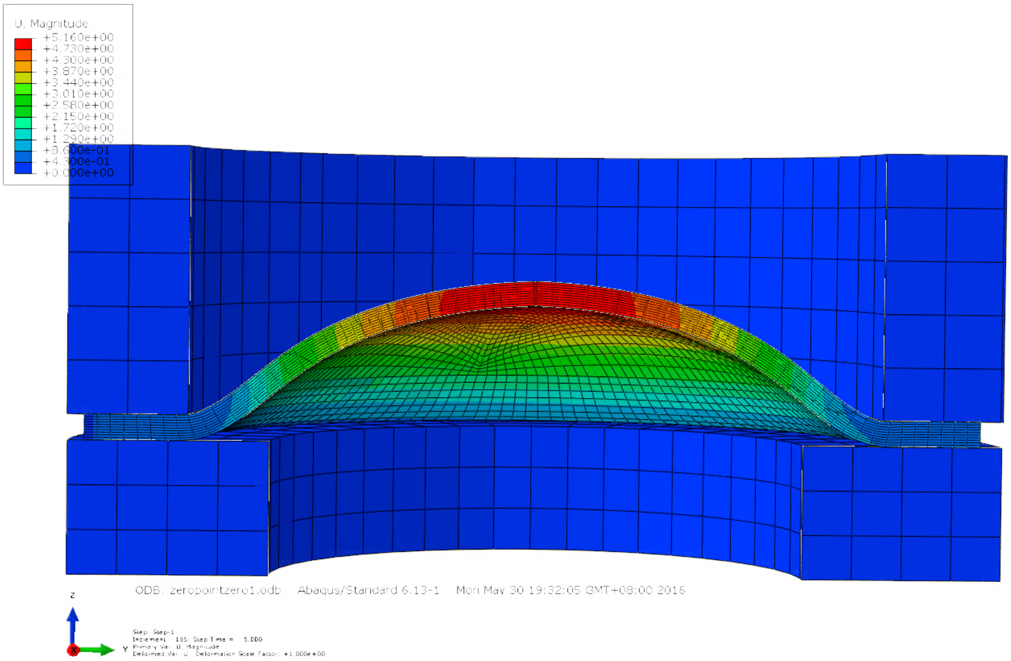

Fig. 6. Hydroforming FEA simulation.

2.2. Process simulation

The limit water pressure during the real hydroforming process is 57 MPa, and the real loading rate which all the experimental rupture disc in this paper was produced with this rate, is shown in Fig. 5. Holding device was set as rigid body to avoid the motion [10]. In this way, the simulation result is shown in Fig. 6.

3. Experimental verification

Eight group of bulging pressure values (50 MPa, 51 MPa, 52 MPa, 53 MPa, 54 MPa, 55 MPa, 56 MPa and 57 MPa) were selected to be analyzed by FEA when all the other factors keep unchangeable. At the same time, two rupture discs were made under each liquid pressure value, as Fig. 7. The real holding device of hydroforming process are shown as Fig. 8 and Fig. 9. This is a free bulging process, and friction coefficient value is 0.01.

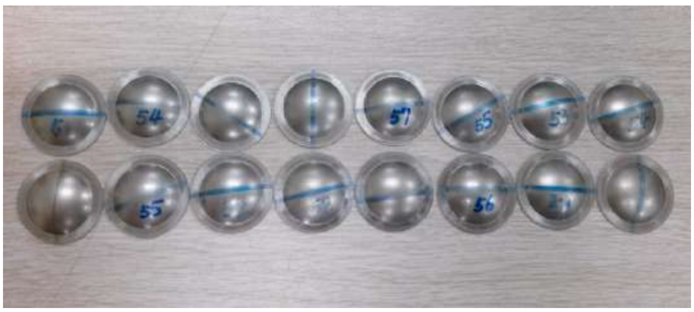

Fig. 7. Samples of eight group bulging pressure values.

Fig. 8. Bottom holding device and rupture disc.

Fig. 9. Top part holding device.

Arch height is the most obvious verification factor which can be easily measured by vernier caliper. Therefore, under different water pressures and real loading rate, arch height of rupture disc in the FEA circumstances and real process were shown as table 1, and it shows that analysis result agreed well with experimental process result.

Table 1. Arch height under different pressures.

P(MPa)	50	51	52	53	54	55	56	57
FEA(mm)	4.86	4.91	4.97	5.08	5.09	5.15	5.20	5.29
Real(mm)	4.86	5.02	5.06	5.05	5.17	5.22	5.27	5.37
Error-rate	0%	2%	2%	1%	2%	1%	1%	2%

In order to evaluate the accuracy of rupture disc top part thinning ratio, rupture disc under 53 MPa water pressure was cut in half through WEDM. Rupture disc's microstructure was measured through the super depth-of-field microscope. The top part thickness of rupture disc is 0.873 mm. FEA result of rupture disc top part thickness under 53 MPa water pressure is 0.888 mm. Original metal sheet thickness is 1mm. Both arch height relative error rate and top part thickness relative error rate is under 5% which is a persuasive data. So the FEA evaluation of this paper is reasonable and can be used in the real production process.

4. FEA optimization analysis

Eight group of bulging pressure values from 50 MPa to 57 MPa were analyzed by FEA. Both arch height value and top part thinning ratio, which is η, increase with the growth of the water pressure, and the results are shown in Fig. 10 and Fig. 11. For the rupture disc in the real working condition, the increase in load-bearing ability due to the strain hardening cannot compensate for the sheet's decrease in the thickness [5].When rupture disc is designed, solely controlled the arch height through the pressure values can lead to the decrease of load bearing ability. If η value is beyond the normal value, rupture disc will burst before working condition reach the predetermined pressure.

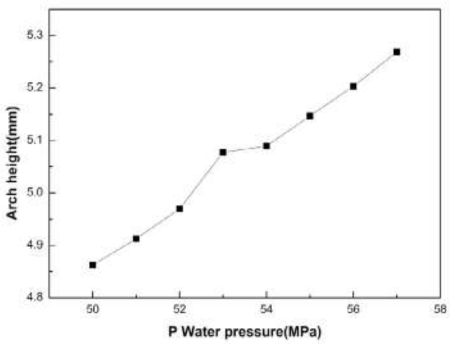

Fig. 10. Water pressure and arch height.

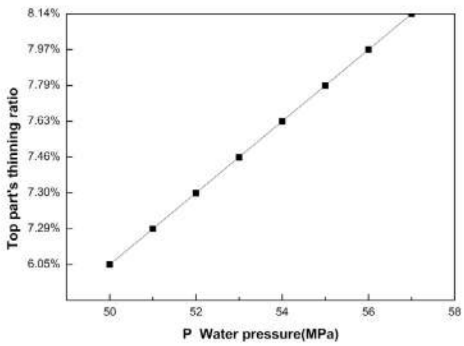

Fig. 11. Water pressure and thinning ratio.

In order to find out the relationship between the friction coefficient, arch height and top part's thinning ratio, when different friciton coefficient values were analysied, other factors keep unchangeable. Under the 55 MPa water pressure and the real loading rate, four friction coefficient values were analysied. Considering the metal flow behavior, with the increasement of friction coefficient value, arch height of the rupture disc decreased and top part thinning ratio η increased. Results are shown in Fig. 12 and Fig. 13. Arch height is directly related to limit burst pressure of the rupture disc .

As a result, when friction between the rupture disc and holding device reduced, arch height increased and η value decreased. In the real hydroforming progress, by changing the lubrication condition of the contact face, arch height of rupture disc and top part thinning ratio can be changed without the increase of the bulging pressure.

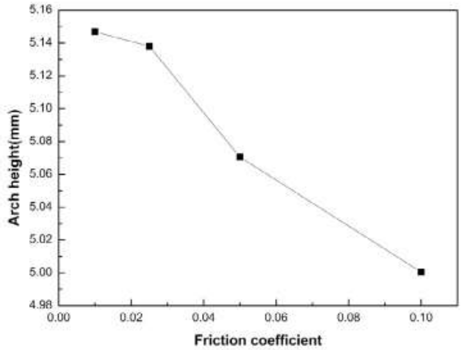

Fig. 12. Friction coefficient and arch height.

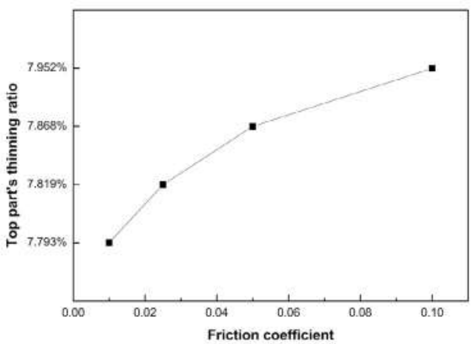

Fig. 13. Friction coefficient and thinning ratio.

Bulging pressure is 55 MPa and under real loading rate, friction coefficient value is still 0.01. Five different linear loading rates and their specific pressure rise-time, which named as A, B, C, D ,E are shown in Fig. 14. With 0.2 s of rise-time, A is the fastest and E is the slowest. As it is shown in Figs. 15 and 6, A is the fastest loading rate and the thinning ratio is the biggest too, but arch height did not go up linearly with the increase of loading rate. Loading rate of C can achieve a better arch height value. It means in the practical hydroforming process, there is a suitable loading rate in which the arch height of the rupture disc can reach the optimum value. Therefore, it is feasible to change the arch height of the rupture disc by changing the loading path.

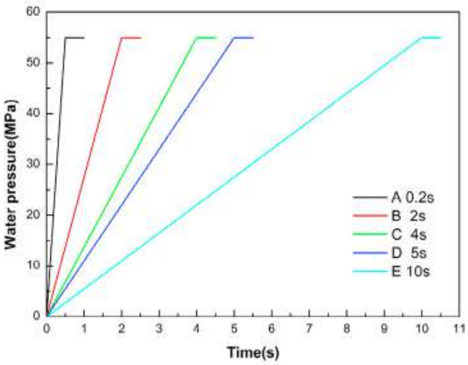

Fig. 14. Five different linear loading rate.

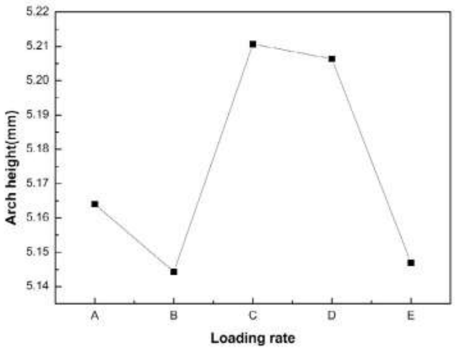

Fig. 15. Loading rate and arch height.

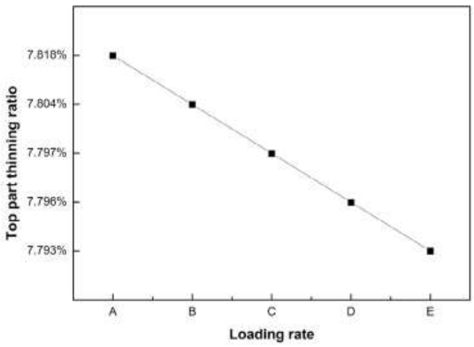

Fig. 16. Loading rate and thinning ratio.

5. Conclusions

In this study, real hydroforming process for rupture disc was carried out experimentally and finite element analysis result agreed well with experimental results which showed the rightness of the whole FEA rupture disc structure optimization. Through the evaluation of FEA, the following results were obtained.

When rupture disc is designed, arch height increased with the increase of pressure values, but solely controlled the arch height through the pressure values can lead to sheet's decrease in the thickness and make rupture disc fail before working condition reach the predetermined pressure.

In the real hydroforming progress, by changing the lubrication condition of the contact face, arch height of rupture disc and top part thinning ratio can be changed without the increase of the bulging pressure. The decrease of friction can reduce the rupture disc thinning ratio and increased the arch height.

In the practical hydroforming process, in order to seek the suitable loading rate to achieve the optimum value of the arch height of the rupture disc, the arch height of the rupture disc can be changed by different the loading path.

Thus, dimensional accuracy of the rupture disc can be ensured and it is possible to predict the thickness, thinning ratio and arch height of the rupture disc through finite element analysis, which is critical for the rupture disc to burst in the predetermined pressure.

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