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Failure Analysis of a Reactor after Explosion Accident

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Abstract

Burst of a reactor occurred in an explosion accident during the production of antistatic agent process. According to the results of site survey, the current regulations and standards as well as the requirements of the accident investigation group, the reason of burst was discussed by failure analysis of the shell and bolts. The shell strength was analyzed by visual inspection, thickness measurement, and strength verification as well as estimating of bursting pressure. It can be concluded that the tank strength met the requirements of design condition. The bolts of the reactor was broken in the accident, so the failure analysis of bolts was carried out in detail, including visual inspection, fracture examination, chemical composition analysis, mechanical testing and strength verification. According to the results of the measured mechanical properties, the strength of the bolts was verified. It can be concluded that the bolts could bear the proof pressure test safely. Fracture analysis shows that no obvious metallurgical defects were found, the bolts were broken due to extreme overload. According to the technical analysis of the shell and the bolts, it can be concluded that the reactor could service safely under normal operating conditions. The cause of the bursting was transient extreme overpressure.

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Keywords: reactor; burst; bolt; fracture; explosion

1. Introduction

An explosion and combustion accident occurred in an antistatic workshop during the process of production. In the accident, a reactor exploded and then the whole workshop was burned-out, see Fig. 1. 2 workers were killed in the accident and 4 were seriously injured, the direct economic losses were about 8,540,000 Yuan. In order to analyze

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the original service situation of the reactor, according to the requirements of the accident investigation group, the reactor was studied by methods of fracture analysis, chemical composition analysis and mechanical test etc.

The reactor was installed on the second floor by lifting lugs. In the accident, the reactor was divided into 2 parts from the flanges. The lower part of the reactor (shell and bottom head) crashed into the ground, resulting in a pit of about 1 m deep, see figure 2. It can be seen that there were 44 bolt holes in the flange, and it is visible that all bolts were installed. Along with the accident rescue, some components had been cleared from the accident scene. Therefore, only 5 pieces of bolts of the reactor were found. The upper head of the reactor flew into an adjacent factory, resulting in a hole in the bounding wall. It is also visible that the bolts had been installed on the flange of upper head.

Fig. 1. The burned-out workshop.

Fig. 2. Lower part of the reactor.

According to the product delivery documentation, the reactor was built in January 24, 2011, and the installation was completed in August 5, 2011. The basic parameters of the reactor are shown in table 1.

Table 1. Basic parameters of the reactor

Serial number		2010450-1
Design pressure		0.8MPa
Working pressure		0.6MPa
Design temperature		220℃
Working temperature		200℃
Medium		Nitric acid, ethylene oxide, tertiary amine
Design service life (normal condition)		15 years
Corrosion allowance		0mm
Shell material		06Cr19Ni10
Bursting pressure of rupture disc		0.66MPa
Internal diameter		1400mm
Capacity		3.3m^3
Nominal thickness (shell/head)		10mm/10mm
Calculated thickness (shell/head)		4.43mm/4.42mm
Stud bolts	Specification	M24×180mm
	Quantity	44
	Material	35CrMoA
	Standard	JB/T 4707-2000

According to the requirements of accident investigation group and the current laws & regulations, the shell and bolts of the reactor were analyzed. The main basis of the analysis includes: requirements of accident investigation group, ***Supervision Regulation on Safety Technology for Stationary Pressure Vessel*** (TSG R0004-2009), ***Steel pressure vessels*** (GB 150-1998). The main methods used in the analysis include field investigation, data review, sample analysis etc.

2. Strength analysis of shell

2.1. Visual inspection

The lower part of the reactor took out from the pit is shown in Fig. 3. It can be seen that the shell was bulged under high pressure. However, no crack appeared in the shell. The deformation of upper end of the cylinder is smaller due to restriction of flange. The planner of the flange leaned inward. Instability occurred in the bottom head due to hitting onto the ground. The maximum circumference of the deformed cylinder is 5020 mm, and the diameter is 1598 mm accordingly. The outer diameter shown in the product delivery documentation is 1420 mm, an increase of 178 mm occurred.

The upper head of the reactor was distorted, as shown in Fig. 4. 7 of the 9 nozzles had fallen off completely, and the remaining 2 nozzles were distorted and torn.

Fig. 3. Lower part of the reactor.

Fig. 4. Upper head.

2.2. Thickness measurement

Draw a line through the center of the nameplate, and then 3 parallel lines, dividing the shell into 4 identical parts. According to thickness measurement along the lines, the minimum thickness is 7.9 mm, and the maximum is 9.3 mm. The minimum thickness of the upper head is 9.2 mm.

According to the strength calculation of reactor in the product delivery documentation, the calculated thickness of shell is 4.43 mm, and 4.42 mm for head. The calculated thicknesses are much lower than the measured thicknesses. It can be concluded that although there were wall thinning in different degrees, the remaining wall thickness is much larger than the calculated thickness.

Conclusions can be made from the results of visual inspection and thickness measurement that the strength of the shell meets the design requirements.

3. Failure analyses of bolts

During the accident, the bolts were broken. Therefore, failure analyses of the bolts were conducted in this paper. According to the product delivery documentation and the results of visual inspection, there should be 44 bolts on the reactor. However, only 5 pieces were found. Give number 1#~5# to the pieces, and the 5 pieces of bolts were tested and inspected.

3.1. Visual inspection

It can be seen from Fig. 3 that the reactor flange had been deformed. That is the bolts were under tensile and bending stresses during the explosion. The 5 pieces of bolts found on site had been corroded. The morphology and size of the bolts after cleaning are shown in Fig. 5.

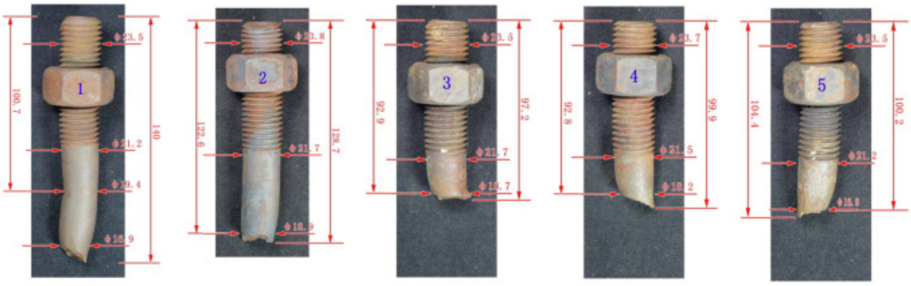


Fig. 5. Size of the bolt pieces.

It can be seen from Fig. 5 that the fracture occurred at the no-thread part. The 5 pieces cannot be fit mutually, indicating that they are independent pieces. Among the pieces, the longest is 140 mm and the shortest is 97.2 mm. The diameter of thread section is 23.5 mm. Other physical characteristics are shown in Table 2.

Table 2. Size and shape of the bolt pieces.

Bolt piece	1#	2#	3#	4#	5#
Total length / mm	140	128.7	97.2	99.9	104.4
Diameter of no-thread section / mm	21.2	21.7	21.7	21.5	21.2
Diameter at the rupture / mm	16.9	18.9	18.7	18.2	16.9

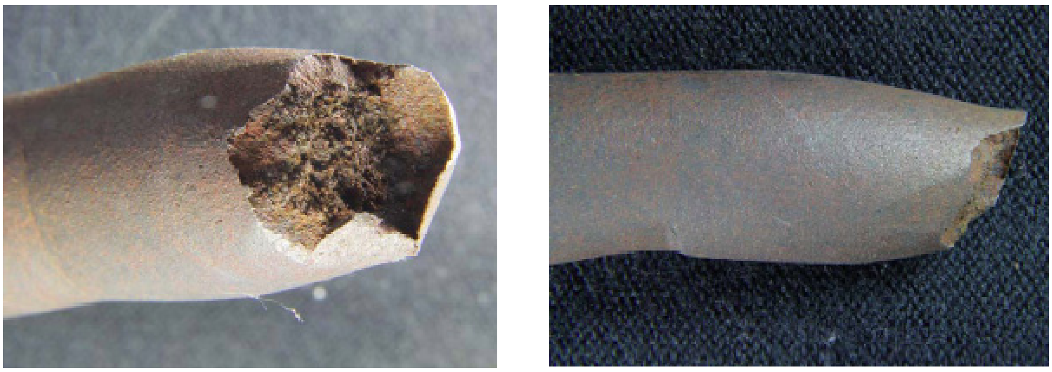
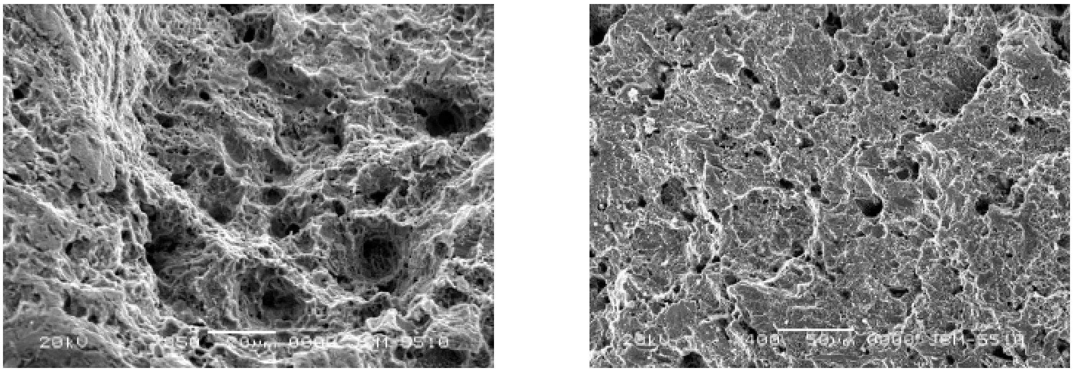


Fig. 6. Fracture morphology of 1#.



(a) Fracture center (b) Fracture edge

Fig. 7. Scanning electron micrographs of 1#.

3.2. Fracture morphology analysis

Fracture morphology analysis and scanning electron microscopy analysis were conducted for the 5 bolt pieces. The pictures of 1# are shown in Fig. 6 and Fig. 7.

It can be seen from the macroscopic examination that, there were no obvious metallurgical defect at the fracture. There was obvious fracture tightening in 1#, indicating that the bolt was overloaded. The tensile shrinkage region of 2# is large, showing large plastic performance. 3# shows the same failure characteristics as 1#. 4# and 5# show inclined tensile fracture morphology.

According to the results of scanning electron microscopy analysis, the 5 bolt pieces show dimple fracture, and the edge show tearing dimple fracture.

It can be concluded that the bolts were broken due to overload. The bolts were bearing tensile and bending load while cracking. There are no obvious metallurgical defects at the fractures.

3.3. Chemical composition analysis

Apply spectral analysis to the 5 bolt pieces. The chemical compositions of the bolts are shown in table 3. It can be concluded that the compositions are similarly to 45 steel. That is different from the 35CrMoA steel shown in the as-built drawing. Also there was no material substitute record.

Table 3. Chemical composition of the bolt pieces (wt%)

Bolt piece	C	S	Si	Mn	P	Cr	Ni	Cu	Mo
1#	0.46	0.012	0.23	0.61	0.023	0.019	0.018	0.009	<0.005
2#	0.49	0.018	0.20	0.60	0.012	0.024	0.018	0.006	<0.005
3#	0.48	0.021	0.28	0.60	0.021	0.010	0.015	0.006	<0.005
4#	0.48	0.010	0.19	0.58	0.013	0.069	0.048	0.14	<0.005
5#	0.47	0.011	0.22	0.61	0.027	0.020	0.019	0.009	<0.005
45 steel[1]	0.42~0.50	≤0.035	0.17~0.37	0.50~0.80	≤0.035	≤0.25	≤0.30	≤0.25	/
35CrMoA[2]	0.32~0.40	≤0.025	0.17~0.37	0.40~0.70	≤0.025	0.80~1.10	≤0.30	≤0.25	0.15~0.25

3.4. Mechanical test

1) Tensile testing

Due to limitation of test pieces, 2 longitudinal samples for tensile test were taken from the thread section of 2# and 5#. The lengths of the samples were 40 mm and 30 mm respectively, as shown in Fig. 8. The results of tensile test are shown in table 4.

Fig. 8. Test samples of 2# and 5#.

Table 4. Results of tensile test

Bolt piece	Yield strength MPa	Tensile strength（R_m） MPa	Elongation(A) %	Reduction of area (Z) %
2#	433（$R_{p0.2}$）	661	19.7	44.5
5#	672（R_{eL}）	731	10.3	43.3
Grade 8.8 Bolt (d>16mm)[3]	660	830	12	52
35CrMoA Bolt (M24~M36)[4]	≥685	≥805	≥13	≥47

2) Impact test

2 impact specimens were prepared from 3# and 4#, and the size is 10mm×10mm×55mm. The results of impact test (KV_2/J) are 12J for 3# and 16J for 4#.

According to the results of mechanical test, the minimum tensile stress is 661MPa, the minimum yield strength is 433MPa, and the impact energy is 12J. The bolts do not meet the 8.8 grade high strength bolt (d>16mm) requirements.

3.5. Strength verification

Due to lack of data of mechanical properties of materials at design temperature, the results of tensile strength and yield strength at room temperature are used for strength verification. Both pre tightening condition and proof pressure test condition are verified. The calculation processes are omitted in this paper.

The allowable stress is:

$$[\sigma]_b=433/2.5=173.2\text{MPa}$$

The minimum area needed for pre tightening condition is:

$$A_a=W_a/[\sigma]_b=2494189.9/173.2=14000.6\ \text{mm}^2$$

The minimum area needed for proof pressure test condition is:

$$A_p=W_p/[\sigma]_b=1989794.2/173.2=11488.4\ \text{mm}^2$$

$$\max(A_p, A_a) = 14000.6\ \text{mm}^2$$

The total area of bolts is:

$$A_b = n\frac{\pi}{4}d_1^2 = 44\times0.785\times20.752^2=14874.5\ \text{mm}^2$$

Since A_b>max (A_p, A_a), the strength verification is satisfied. It can be concluded that the bolts meet the requirements of proof pressure test condition.

3.6. Estimation of internal pressure causing cracking of bolts

Due to lack of data of mechanical properties of materials at design temperature, the internal pressure leading to cracking of bolts is estimated using the results of mechanical test at room temperature. The bursting pressure of shell is also estimated. The calculation processes are omitted in this paper.

The calculated internal pressure leading to cracking of bolts is about 3.12MPa. And the bursting pressure of shell is about 5.86MPa. That is why the bolts were cracking, while the shell was deformed but did not crack. It is also a proof of that the reactor was overloaded beyond design pressure, but did not reach the burst pressure of shell.

If the specified bolts were used, that is the material would be 35CrMoA. Then the calculated internal pressure leading to cracking of bolts is about 6.50MPa. That is higher than the bursting pressure of shell. It could be seen from the shell that the reactor was overloaded seriously. However, it is difficult of gain the real internal pressure during the accident. There is no evidence that the specified bolts could prevent the bursting. In that occasion, the burst would occur at somewhere in the shell.

4. Conclusions

According to the analysis results, the following conclusions can be drawn regardless of the factors of management:

1) The reactor was deformed and the wall was thinned due to overload. However, the remaining wall thickness is much larger than the calculated thickness. The strength of the shell meets the requirements of design condition.

2) Fracture analysis results show that the bolts were cracked due to extreme tensile load. There are no obvious metallurgical defects in the bolts. The loads on the bolts while cracking were much higher than that of design condition.

3) It can be concluded according to the strength verification that the bolts meet the proof pressure test condition.

Acknowledgements

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