Fracture Mechanics Concepts to Increase the Reliability of High-pressure Gas Cylinder

E. CZOBOLY*, G. FRIGYES**, I. HAVAS*, J. LOVAS*, GY. SOMOGYI***, L. TOTH**

**TU Budapest, Research Group of Hung. Ac. Sc., Budapest H-1521, Hungary*

***TU for Heavy Industry, Miskolc H-3515, Hungary*

****Csepel Iron and Steel Work, Budapest H-1751 P.O. Box 40, Hungary*

ABSTRACT

Fracture mechanics tests and investigations on crack propagation were performed on high-pressure gas cylinders. The results led to the conclusion that periodically repeated pressure tests garantee the integrity of bottles within the time interval.

KEYWORDS

Gas cylinder; reliability; fracture mechanics; fatigue crack propagation; pressure test.

INTRODUCTION

High pressure gas cylinders are produced in a great quantity, therefore any excess costs are of importance. On the other hand the risk of failure must be kept very low,so their testing methods should be selected carefully to find the balance between reliability and economical production.

Since the manufacturing processes for high-pressure gas cylinders have been recently improved at the Csepel Iron and Steel Work, Budapest this new technology demanded the reconsideration of the testing methods and the inspection processes. The starting point was the ambition of every fair manufacturer, namely:

"To fabricate correctly dimensioned products from an adequate material using a suitable technology."

"Correct dimensioning" means to take accont also of cyclic loads, corrosive media, varying temperature, overloading, possible mounting stresses, forces by transportation, etc. An "adequate" material has the strength and other physical properties demanded, but is the cheapest of all possible variations. "Suitable" technology is not only an economical process, but results in only a small scatter in dimensions and quality and does not permit the occurence of defects.

Of course, these ideal requirements cannot hardly be met, therefore inspection of the products during and after the manufacturing process is necessary. Inferior goods must be repaired or scrapped. However there is the everlasting problem: where is the limit between the acceptable products and those to be rejected. In the past this judgement was based in most cases on experience, or on convention. Now fracture mechanics provide a much more exact way.

PROBABILISTIC APPROACH.

It is a well known fact that there are defects in every product. The dimension and distribution of the defects are different and depend on the material, technology, skill of workers and many other factors. Theoretical considerations supported by ultrasonic inspection resulted exponential distribution functions (Marshall,1976; Nilson,1977; Wellein,1981) similar to the curves A and B in Fig.1.

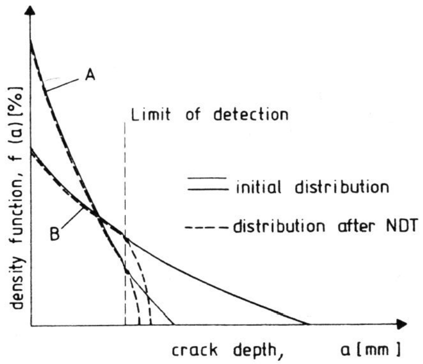

Fig. 1. Distribution of defects before and after NDT in two different work pieces.

Using any NDT method, some of the defects can be detected. However every method has its own limitation and therefore only defects greater than a given size can be revealed. Even within this range the detection of defects has a certain probability which increases with the size of defects but never reaches the value of one. So, defects will remain after any combination of

NDT methods, only the probability of their occurance will decrease. This is shown schematically by the dotted lines in Fig.1. If more accurate NDT methods are applied the number and sizes of the remaining defects will decrease and so the safety factor can be reduced.However, this increases the time and expenses of the production.

If the dimensioning of the products and the material is specified by codes and the safety factors are given, the NDT methods should be optimized to ensure the detection of the dangerous defects with high probability, but not to interfere with insignificant faults.

THEORETICAL CONSIDERATIONS

Defects may be regarded as "dangerous", if they can induce a fracture or collapse during the service life.An increase of the initial defects by crack propagation due to fatigue or corrosion (or both) can occure. Fracture will be induced, when the size of the crack reaches a critical value, a_{crit}. This value can be calculated on the basis of fracture mechanics

$$a_{crit} = K_{Ic}^{2} \cdot \sigma_t^{-2} \cdot Y^{-1} \qquad (1)$$

where K_{Ic} is the fracture toughness of the material, σ_t is the hoop stress and Y is the geometrical factor.

If alternating loading is characteristic for the work piece - as it is in the case of gas cylinders - crack propagation should be considered to assess the admissible defect size (a_o). One simple law has been recommended by Paris and Erdogan (1963).

$$da/dN = C \cdot \Delta K^{m} \qquad (2)$$

where da/dN is one step of crack propagation per load cycle, ΔK is the range of stress intensity factor due to the alternating stress, C and m are coefficients to be measured. Unfortunately, C and m are not real material parameters, but they depend also on the assimetry factor of loading,R, on the kind of stresses, etc. However, under given conditions Equ.(2) provides the possibility of a reasonable engineering assessment.

EXPERIMENTS AND CALCULATIONS

To determine the critical crack depth in this particular case the quantities occuring in formula (1) should be known. Fracture toughness of the material is one of the basic data. This was measured by different methods. Although the geometry of the work piece, having a wall thickness of about 5 mm and a cylindrical shape with a diameter of 200 mm and the relatively tough material with a yield stress of 560 MPa, UTS 700 - 800 MPa and RA 54 % did not allow to accomplish valid fracture mechanics tests, compact specimens were machined and tested. The fracture toughness was calculated according to the ASTM E399 Standard. The result was: $K_{Ic} = 2362\ Nmm^{-3/2}$

The fracture toughness was determined also by the extrapolating method (Radon and Czoboly,1972; Czoboly et.al,1976) using small, cylindrical, notched tensile specimens. These experiments yielded δ_c = 0,05 mm ,which is equivalent to K_{Ic} = 2530 $Nmm^{-3/2}$.

Finally the bottles were notched in the axial direction and then pressurized up to fracture. The dimensions of the artificial defects and the bursting pressures are given in Table 1. One of the broken bottles can be seen in Fig.2. Although even this long and deep notch did not result a real brittle fracture,the toughness has been calculated using the formulae of Newman and Raju (1979), modified by Kieselbach (1986):

$$K_{Ic} = \sigma_{t\,crit} \cdot \sqrt{\frac{\pi a}{Q}} \cdot F \qquad (3)$$

where $\sigma_{t\,crit}$ is the hoop stress at the moment of frature, Q is a factor for half-elliptical surface cracks and F a factor depend- ing on the ratios of a/t and a/c. Here a and c are the half-axes of the half-ellipse and t is wall thickness. The average of these experiments resulted 2708 $Nmm^{-3/2}$,which is somewhat above those measured on specimens but considering the fact that instead of cracks artificial notches were applied, the agreement is satisfactory.

Table 1. Dimensions of notches and bursting pressures.

Notation of Bottles	Wall Thick-ness,t (mm)	Notch Depth a (mm)	Notch Length 2c (mm)	Bursting Pressure (bar)
1	6,1	1	92	440
2	6,2	2	96,5	400
3	6,5	4	107	200
4	6,15	2	96,5	380
5	6,25	4	107	200

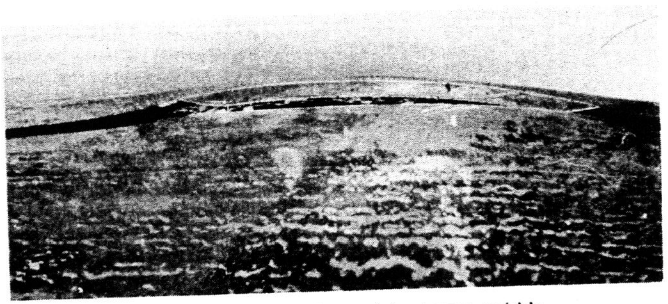

Fig. 2. One of the gas cylinders with artificial notches after bursting test.

The mean value of all fracture toughness measurements was 2500 $Nmm^{-3/2}$ and the lowest toughness, which occured was round 2000 $Nmm^{-3/2}$. In the following calculations both values were used.

The next quantity to be determined was the hoop stress, σ_t. This depend on the internal pressure and the wall thickness. The pressure in service varies between 0 and 150 bar (p_1), while at the pressure test applied after manufacturing and at intervals it is 225 bar (p_2). The scatter of wall thickness is high. To cover this range t = 5; 5,5; 6 and 6,5 mm was selected. So, 8 different stress values were calculated by the well known formula:

$$\sigma_t = \frac{D\,p}{2t} \qquad (4)$$

where D is the diameter of the bottle.

Next a most unfavourable crack geometry was chosen to provide a conservative calculation. An axial crack 2c = 1500 mm long (total length of the cylinder) starting from the inner surface and extending in radial direction has been assumed. Since the factors Q and F in Equ.(3) are depending on a/c, σ_t/R_e and a/t, K_I values were calculated numerically in the function of a and were plotted in diagrams using the parameters p and t. This can be seen in Fig. 3. K_{Ic} values are also marked in the figure determining the critical crack depths (a_{crit}).

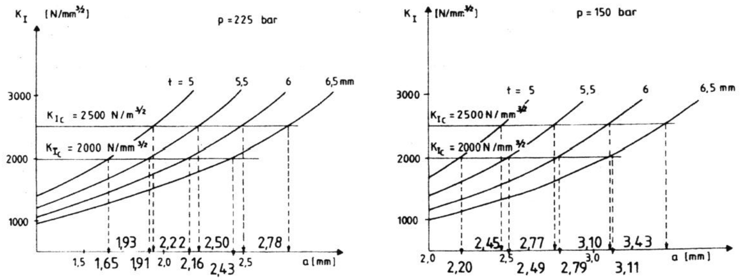

Fig. 3. Stress intensity factors of gas cylinders with axial surface cracks. K_{Ic} determine the a_{crit} values.

Considering only the pressure tests all defects smaller than the a_{crit} values (2c = 1500 mm, p_2 = 225 bar) will remain undetected.Some bottles (namely with greater defects) will fail,the others will be accepted. These a_{crit} values are shown by the full lines in Fig.4. In extreme case, such defects should be taken into account and regarded as potential a_o values for bottles getting in service. Because of the alternating pressure between 0 and 150 bar the cracks may propagate in service by fatigue and if they reach the a_{crit} values for p_1 = 150 bar (dotted lines in Fig.4.) the bottles will fail.Such an accident should be avoided with a high security! Therefore, crack propagation by fatigue was also investigated.

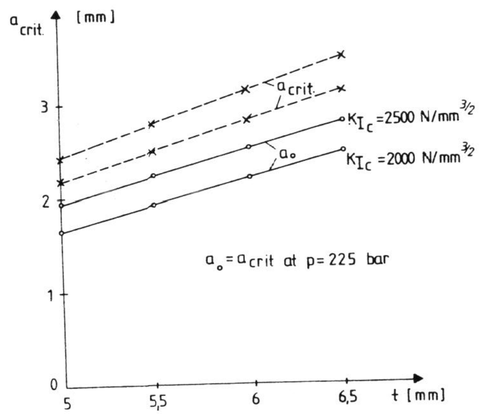

Fig. 4. Assumed initial cracks after the pressure test (a_o) and the critical crack depths (a_{crit}).

In the first part of this work, compact specimens were used and the C and m parameters of the Paris equation determined. Stress ratios,R between 0,15 and 0,5 were applied. The results were extrapolated to R = 0, which yielded C = $1,7276.10^{-19}$ m = 5. The number of cycles required to propagate a crack from a_o to a_{crit} can be calculated by integrating the propagation law

$$N = \int_0^N dN = \int_{a_o}^{a_{crit}} \frac{da}{C\,\Delta K^m} \qquad (5)$$

where ΔK depends on the alternating pressure, the wall thickness, the crack geometry,the crack size and the a/t ratio. N was calculated for all the assumed cases and the results are given in Table 2.

Table 2. Number of cycles required to propagate a crack from a_o to a_{crit} .

K_{Ic} ($Nmm^{-3/2}$)	t (mm)	σ_t(MPa)	a_o (mm)	a_{crit} (mm)	N (10^4)
	5	225	1,93	2,45	2,65
2500	5,5	205	2,22	2,77	3,23
	6	188	2,50	3,10	4,08
	6,5	173	2,78	3,43	5,19
	5	225	1,65	2,20	3,92
2000	5,5	205	1,91	2,49	4,71
	6	188	2,16	2,79	5,82
	6,5	173	2,43	3,11	7,24

In the second part of this work four bottles were loaded by cyclic internal pressure, previously notched by electric erosion The axial notches were 1500 mm long, 2 mm deep and 0,15 mm wide. The number of cycles up to fracture were 3428, 4234 and 5276. The bottles are shown in Fig.5.

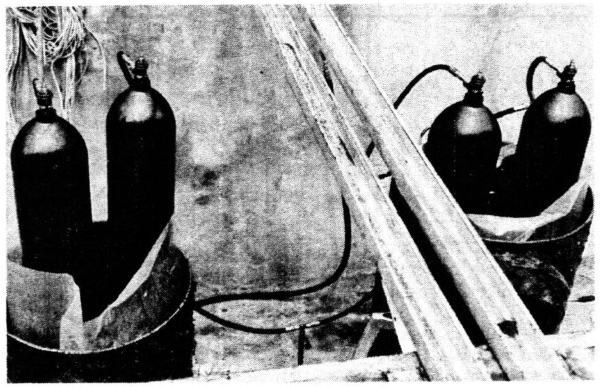

Fig. 5. Testing arrangement for cyclic internal pressure.

Comparing the results of the direct measurements and of the calculation based on the data obtained by specimens, a ratio of about 1 : 10 was found. The calculation is non-conservative. This difference can be explained by several reasons. First, the crack propagation does not follow Paris-equation near the critical crack size. Secondly, the material at the fatigue crack tip will be deteriorated by the cyclic loading, therefore the fracture will be induced by a smaller crack than calculated. This incertainties justifies the general practice that a safty factor of 20 is used for service life. On the other hand it can be stated that the pressure test ensures a satisfactory safety against unexpected accidents of the bottles, because the maximum number of cycles in service is 50 per year.

High pressure gas cylinders are inspected by ultrasonics after manufacturing, because of the prescriptions of the authorities, but periodically repeated pressure tests are more important and garantee the integrity of the bottles.

REFERENCES

CZOBOLY,E., I.HAVAS and J.C.RADON (1976). Fracture Evaluation at High Loading Rates by the Extrapolating Method. in: Proc.Dynamic Fracture Toughness London (M.G.Daves, ed.) pp.159-167.The Welding Inst.,Abbington Hall

KIESELBACH,R., (1986) Fehlertiefe von nachtlosen Hochdruck - Gas- flaschen. Material und Technik. No.1.pp.3-12.

MARSHALL,W. (1976) An Assessment of the Integrity of PWR Pressure Vessels. Report of UKAEA.

NEWMAN,J.C. and I.S.RAJU (1979). Analysis of Surface cracks in Finite Plate Under Tension or Bending. NASA-TP-1578.

NILSON,F. (1977). A Model of Fracture Mechanical Estimation of the Failure Probability of Reactor Pressure Vessels. Proc. 3rd Int.Conf.on Pressure Vessel Technology. vol.II.pp.593-601.

PARIS,P.C. and F. ERDOGAN (1963). A Critical Analysis of Crack Propagation laws. J.of Basic Eng. Trans. ASME Series D. vol.85. pp.528-534.

RADON,J.C. and E.CZOBOLY. (1972). Material Toughness Versus Specific Fracture Work. Proc.Int.Conf. on Mech.Behaviour of Materials. Kyoto, Japan, vol.1.pp.543-557.

WELLEIN,R. (1981). Assessment of the Reliability of Primery Components of a Pressurized Water Reactor by Probabilistic Fracture Mechanics. in: Proc. 5th Int. Conf. on Fracture. Cannes (D.Francois ed.) vol.5.pp.2109-2117. Pergamon Press,Paris