Structural Reliability Tests of Reactor Vessels During Destructive Tests of Models

Alexander A. Blumin
TZNII KM "Prometei", Leningrad, USSR
Yuri G. Dragunov
OKB "Gidropress", Moscow, USSR
Igor V. Gorynin, Victor A. Ignatov, Georgii P. Karzov, Boris T. Timofeev
TZNII KM "Prometei", Leningrad, USSR

INTRODUCTION

Large scale model and full-scale vessel destructive tests with simulation of principal calculation situations are carried out, as a rule, at the stage of completion during substantiation of accepted standard approaches used for the integral strength verification and substantiation of equipment life.

MATERIALS UNDER INVESTIGATIONS AND INVESTIGATION METHODS

To perform tests to loss of tightness under cyclic conditions scale models of 12XIMФ, 15X2MФA, 15X3HMФA steels were fabricated. Nozzle-to-vessel weld performed by various process versions was tested. In all more than 10 models with outer diameter of 460 ... 600 mm and wall thickness of 35 ... 40 mm were fabricated. These models were loaded by pulsating internal pressure with a frequency of 1 cycle for 3 min when minimum pressure of 3,5 ...5 MPa and maximum pressure of 20-25 MPa in a cycle are provided. Tests were conducted at medium temperature of 20°C with strain gauging areas with maximum stress concentration and estimation of effective values of strain concentration factor by the moment of fatigue crack arising. Number of cycles corresponding to loss of tightness of a model was the moment of test completion. Then failure surface and area of crack initiation as well as variation of mechanical properties of model metal were studied.

To evaluate the serviceability of weldment that connects WWER1000 reactor vessel to Dy 850 pipeline and performed by manual arc welding on site without subsequent heat treatment test of full-scale model /1/ of nozzle area of 15X2HMФA steel was performed. After life tests of this model according to conditions Pmin= 4 MPa and Pmax = 25 MPa for $5 \cdot 10^3$ cycles and check of model integrity by nondestructive tests in the area of thermally non-treated weld in the axial and circumferential direction on the outside were performed notches with 12 mm depth. Configuration of notches corresponded to surface semi-elliptical crack. The model has been loaded by pulsating internal pressure at temperature of 20°C according to conditions Pmin= 4 MPa and Pmax = 28 MPa for 10^4 cycles and then the model was broken down in the cooled state to -20°C by one-fold pressure.

To evaluate brittle failure strength of WWER-440 reactor vessels, namely,its cylindrical part four models were fabricated. One of the models of the core shell /2,3/ corresponded to plastic state of metal in the initial period of operation, the other one - to brittle state due to the effect of special heat treatment on metal (undertempering - simulation of metal state at the end of service life). In two models with circumferential welds in the shell middle part made by one process the difference lies in the fact that one of them was completely heat treated after welding according to tempering conditions at 660°C for 15 hours and the other - embrittling tempering at 620°C for 6 hours. Before tests all 4 models were notched for various depth and length.

TEST RESULTS AND THEIR DISCUSSION

Tests of models with various ways of nozzle connection to a vessel under cyclic conditions showed that destruction is always initiated in the area of maximum strain concentration,i.e. in the point of intersection of generatrices of vessel and nozzle cylinders. Having known the amplitude of strain at this point (by the calculation or experiment) the moment of fatigue crack arising in the model may be predicted with adequate accuracy by the results of tests of specimens of the same heat. This fact is indicative of legitimacy of using the strain criteria of low cyclic failure at estimation of large structures life.

After operational-life proof of full-scale model of WWER-1000 reactor nozzle area no fatigue failures were revealed. Subsequent test of this model with electro-arc notches according to conditions $4 \rightleftarrows 28$MPa resulted in the fact that after 7.10^3 cycles was recorded an increase of notch edge separation by 0,005 mm. This fact,apparently, is indicative of fatigue crack being initiated from the notch. However, nondestructive control methods failed to determine the value of crack depth increase and tests were continued under the same conditions to 10^4cycles (notch edges separation increased by 0,007 mm)/3/. Further cyclic loading of the model according to conditions of $5 \rightleftarrows 45$ MPa during 5.10^3 cycle resulted in continued increase of separation corresponding to the average rate of fatigue crack growth of $1,3.10^{-6}$ m/cycle (final size of fatigue crack estimated in fracture analysis was 10 mm). Since failure occurred along the weld, in operation the estimation of failure strength was carried out at the stage of crack initiation and extension at 20°C for the weld metal performed by manual arc welding with YOHИ-13/45 electrodes in the initial state /1/. The results of comparison of cyclic strength characteristics during tests of a model and specimens under identical conditions are given in Fig.1. They are indicative of the fact that at the stage of initiation and extension of a fatigue crack durability by the moment of crack arising due to the notch during test of the model and constant "m" of Paris equation determined along the fatigue crack front of nozzle area model correspond to 50% probability of respective characteristic during small specimens testing. This confirms that the characteristics obtained at cyclic loading during specimens testing with sufficient reliability control the behaviour of real structure. Hydrostatic tests of the model were carried out after preliminary cooling by dry carbon dioxide. Model was broken down at pressure of 52,5 MPa due to axial notch. The weld was the initiator of failure (temperature was -20°C, hoop stresses amounted to 407 MPa). Brittle crack propagated to the both sides of the weld. The crack moved into the massive fillet of the nozzle of 15X2HMФA steel for 100...120 mm and stopped and tube of 10ГН2МФА steel failed along the generatrix and the ring near the weld of process plug. Fracture pattern is quasi-brittle since on its surface behind the section with pronounced front of fatigue crack there was an area of 2...6 mm length indicative of remarkable plastic strains taking place in the apex of fatigue crack after one-fold loading to destruction of the model. The value critical coefficient of stress intensity of the model of 85 MPa $\sqrt{m}$ corresponded to about 10% of probability of this characteristic obtained by fracture toughness tests of specimens (Fig.1,c)

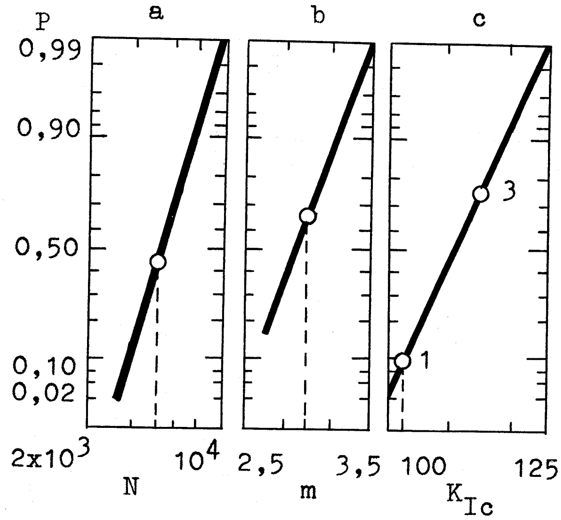

Fig.1. Test results obtained on specimens cut out of weld joints compared to those obtained on a full-scale nozzle-zone model No 1:
a = crack initiation criterion (ε_a = 0,36% t=20°C)
b = crack growth criterion (t=20°C)
c = fracture toughness criterion (t= -20°C)

At hydrocyclic tests of models of 15Х2МФА steel movements of internal edges of notches were recorded with the help of inductive transducer allowing (Fig.2) to determine roughly the moment of fatigue crack initiation from the notch in models Nos 4 and 5. During control by non-destructive method the crack depth was not successful to be estimated and the fact of the crack development had been recorded only after the model failure (crack depth was 0,5...1mm). For models Nos 2 and 3 indications of inductive transducer during internal pressure tests did not change as loading cycles accumulated.

The main loading parameters are given in the table.

Fig.3 represents the results obtained by testing to failure model No 4 with a circumferential weld seam. The value of stress intensity coefficient in the apex of fatigue crack was 88 MPa $\sqrt{m}$ (Fig.3) that is very close to the modal value of K_{Ic} characteristic for weld metal performed by automatic welding under flux layer with wire СВ-10ХМФТ (from 75 to 115 MPa $\sqrt{m}$).

Table

Main loading parameters during model tests to destruction

Tested model	Parameters of cyclic loading			Notch parameters		Static loading parameters			Character of failure
	Pmin, MPa	Pmax, MPa	Number of cycles	a start mm	a end mm	$T_{исп}$ °C	$P_{исп}$ MPa	K_{Ic}, MPa$\sqrt{m}$	
Model No1	4 5	28 45	10^4 5.10^3	– 12	– 22	– -20	– 52,5	– 85^x	Brittle failure due to fatigue crack in axial notch
Model No2	10	39,5	10^4	31	31	-20	112,5	290	Brittle-tough failure due to mechanical notch from the outside of 54 mm depth
Model No3	10 10	39,5 39,5	3.10^3 3.10^3	28 3	28 14	+20 +20	67,0 67,0	105 112^x	Breaking away of the cover due to fatigue crack initi-ed by lack of penetration of 3 mm depth
Model No4	5 5	29 45	10^3 3	– 16	– 20	– +20	– 45,0	– 88	Quasi-brittle failure due to fatigue crack in the weld initiated by the notch of 16 mm depth
Model No5	5	29	$3,9.10^2$	12	13	+20	29,0	51	Brittle failure due to fa-tigue crack in the weld

X - calculated without residual and edge stresses

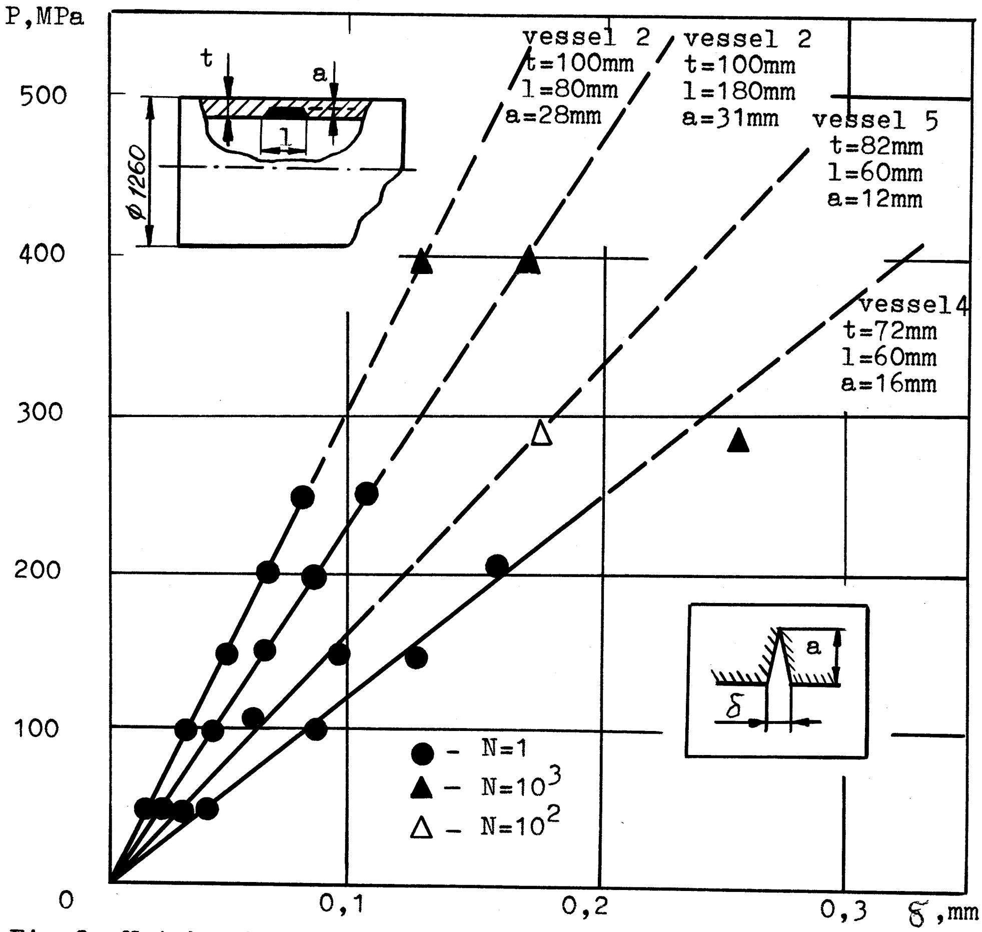

Fig.2. Notch edge displacement in vessel 2,4 and 5 under static and cyclic loading

Fig.4 represents fracture toughness temperature dependence for weld metal in 15X2MФA steel. Fracture toughness of weld metal in this model of 88MPa $\sqrt{m}$ was compared to similar characteristics of weld metal in the embrittled state obtained during specimen tests.

CONCLUSIONS

Low fatigue tests of full-scale models showed the validity of the accepted standard methods for the estimation of serviceability of large structures by criteria of fatigue failure initiation.

Model brittle failure strength tests are indicative of the applicability of fracture mechanics criteria for verification of structural reliability of the reactor vessels when loaded in the temperature area below the critical one and availability crack-like defect of 0,3-0,6 of steel thickness.

The analysis of vessel life shows that welded joints are the most damageable components of vessels.

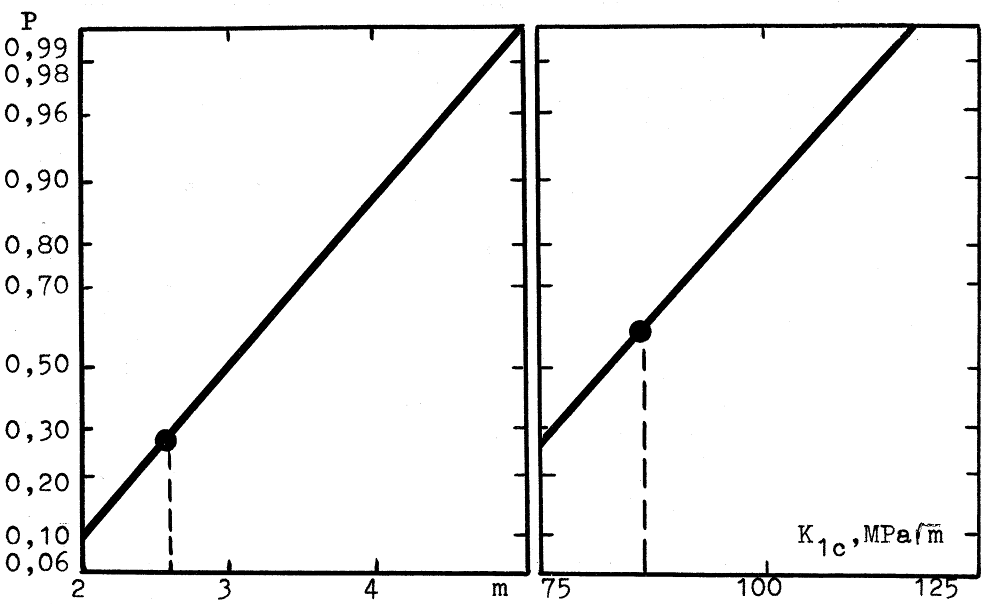

Fig.3. Test results obtained by testing to failure model No 4 completed with a circumferential weld seam

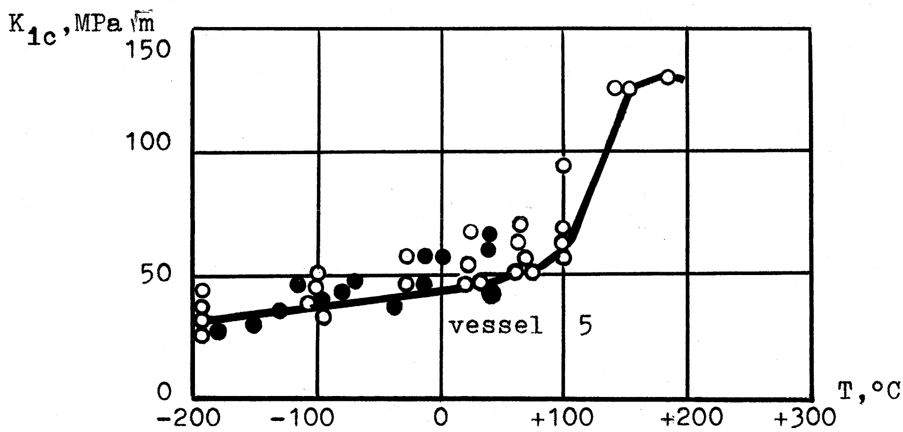

Fig.4 Fracture toughness temperature dependence for weld metal in 15Х2МФА steel: o -after thermal treatment simulation; • - irradiated by neutron fluence $F = 2x10^{23} n/m^2$

REFERENCES

Блюмин,А.А.,Горынин,И.В.,Игнатов,В.А.,Тимофеев,Б.Т. Оценка работоспособности сварных монтажных соединений трубопроводов из теплоустойчивой стали. Автоматическая сварка,1982,№7,с.3-10.

Dragunov,Yu.G., Ignatov,A.A, Karzov,G.P., Timofeev,B.T. Testing to Destruction of Large-sized Models. IAEA Seminar on Large Scale Testing, Stuttgart MPA,FRG,25-27 May 1988, 35 p.

Блюмин,А.А., Звездин,Ю.И., Тимофеев Б.Т. и др. Применение критериев механики разрушения к оценке работоспособности крупногабаритных сосудов высокого давления. Проблемы прочности, 1986,№ 6,с.40-45.