ZJE - 283 1989

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ABSTRACT

This report deals with the verification of fracture mechanics and fatigue calculations for the WWER reactor pressure vessels by large scale model testing performed on large testing machine ZZ 8000 (with maximum load of 80 MN) in the ŠKODA WORKS. In the first part are described the results from testing of material resistance against fracture (non-ductile). Large set of testing has included the base materials and welding joints. Nominal specimen thickness was 150 mm with defects of depth between 15 and 100 mm.

The second part presents results from testing of nozzles with ID 850 mm in scale 1:3; static, cyclic, and dynamic tests have been performed without and with surface defects (15, 30, and 45 mm deep). During cyclic tests the crack growth rate in elastic-plastic region has been also determined.

THE PROBLEMS OF MODEL TESTING

The requirements of nuclear reactor pressure vessels safety and reliability are concentrated, first of all, on ensuring their resistance against brittle and fatigue failures during complex operational loading conditions. As a basis for the calculations of structural resistance against failure serve the standard characteristics of the materials obtained by testing of small standard specimens. Codes and standards for calculation of strength and reliability of pressure vessels and other components of nuclear reactors contain the so-called guaranteed values of individual material characteristics. These values represent, as a rule, the upper and lower bound curves of material properties on the safe side. For some complicated structures where only an approximation method can be used, it is not fully understood whether calculations are conservative or optimistic ones. For this reason the determination may be fulfilled by suitably chosen experiments which serve for precising the up-to-date calculation methods.

Another reason for carrying out the tests of large test specimens (up to thicknesses equal to those of real products) is to eliminate the size effect (material and geometrical) on received results.

The "material size effect" represents the existence of non-homogeneity of properties and structure of material, of residual stresses, of statistical distribution of defects in the material, etc.

The "geometrical size effect" represents the effects of defect configuration and of the ratio between the defect, plastic zone, specimen size, etc.

From these reasons a wide program of large scale model testing is carried out in the ŠKODA WORKS to ascertain the real safety margins of the pressure vessels for the WWER-440 and WWER-1000 MW reactors which are produced by the ŠKODA WORKS.

THE TESTING OF BRITTLE FRACTURE

The testing of large test specimens with testing section of 150x600 mm (fig. 1) has been used to get the answers on:

- the reproducibility of results, i.e. checking of stress-strain specimens with respect to defect size and finite specimen dimensions
- the conditions of failure in elastic-plastic conditions of loading
- the variability of failure conditions with respect to material properties, type of material and of welding joint.

The strain field in specimens with a defect

The strain fields in specimens have been measured in 50 points by strain gauges in different positions - from the vicinity of crack tip to specimen edges.

The measurements in crack plane on specimen surface (axis y) show that the results are in a good agreement with theoretical dependence between strain and distance from crack tip (for distances larger than the plastic zone size) given by the formula

$$\varepsilon_x = \varepsilon_{nom}\left(\frac{a}{2\,y}\right)^{1/2} + \varepsilon_{nom} \qquad (1)$$

where a denotes crack depth. Received results for specimens from the Cr-Mo-V type of steel of the 15Kh2MFA grade for example for point "C" in the distance of 10 mm from crack tip are shown in fig. 2. The dependence between crack size and measured strain is well described by formula (1) where the exponent in fig. 2 is equal to 0.42, which is very close to the theoretical value of 0.5.

Further measurements have shown that specimen width does not affect the results obtained, as strains in point "B" are practically equal to the nominal values for all crack length up to 2c = 300 mm (i.e. up to 50% of specimen width).

The measurement in point "A" has shown that finite thickness of specimens plays a role for crack depth equal to or larger than one third of specimen thickness, which is also in a good agreement with calculations for corrections on thickness.

Fracture parameters

The main reason of these tests is to ascertain failure conditions of tested materials with surface semielliptical defects. Materials under study are given in tables 1 and 2:

TABLE 1 Chemical Composition of Materials (wt.%)

material	C	Mn	Si	P	S	Cr	Ni	Mo	V
15Kh2MFA Steel	0.15	0.48	0.35	0.013	0.016	2.77	0.14	0.60	0.34
S/A Weld Metal	.16	.40	.25	.012	.015	2.78	.16	.69	.30
ES Weld Metal	.18	.47	.26	.013	.013	2.70	.15	.61	.31
15Kh2NMFA Steel	.13	.41	.23	.010	.018	2.06	1.32	.63	.07

TABLE 2 Mechanical Properties of Materials at 20 °C

material	$R_p0.2$	R_m	A_5	Z	KCV	T_{ko}	K_{IC}
	MPa	MPa	%	%	$J.cm^{-2}$	°C	$MPa.m^{1/2}$
15Kh2MFA Steel	575	680	21.2	72.8	210	-30	150÷200
S/A Weld Metal	425	565	25.4	66.4	30	+30	80
ES Weld Metal	550	665	20.4	73.0	30	+30	80
15Kh2NMFA Steel	570	660	21.4	70.0	200	-30	220÷250

Tests of large specimens (150 mm thick) have been carried out on the ZZ 8000 testing machine in the region of elastic-plastic conditions of loading, i.e. in the interval of $T_{ko}\pm50$°C, where T_{ko} is the transition temperature called "Critical temperature of brittleness"[1] according to the Interatomenergo Standard 38.443.51-84, and is determined using the Charpy-V notch impact tests.

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[1] The transition temperature T_{ko} is defined as follows:

- at the temperature of T_{ko} the mean value of KCV from three tests is equal to 60 $J.cm^{-2}$ (for steels with yield strength in interval between 550 and 700 MPa);

- at the temperature equal to T_{ko} + 30° the mean value of KCV from three tests must not be lower than 90 $J.cm^{-2}$ and the mean value of the brittle fracture appearance must not be larger than 50%.

There are also supplementary requirements for the lowest values of KCV of individual tests and for repeated testing. This transition temperature lies within the interval of $RT_{NDT}\pm10$°C, as has been demonstrated for both types of steels.

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The results obtained for the 15Kh2MFA type of steel are summarized in fig. 3, which contains not only results from large specimens (150x600 mm) but also results from smaller ones. All their dimensions have been reduced in scale 1:8 or 1:12 in comparison with large ones, i. e. their thicknesses have been 18.75 or 12.5 mm, respectively. Their testing temperatures have been chosen between -196 and +20 °C, and the tests have been carried out on MTS 2.5 MN testing machine. The results for crack depths equal to 3, 5.5 and 11.3 mm have been obtained by testing small scale specimens, while crack depths 40 and 100 mm belong to large scale specimens.

For comparison the temperature dependence of crack arrest temperature for this type of steel with a thickness of 150 mm, received in previous research program, has also been added in fig. 3. These ESSO type tests with temperature gradient in specimen width equal to 1,200 mm were carried out also on the ZZ 8000 testing machine. During these tests crack propagation and arrest have been performed in constant stress field.

Analysing the "Fracture Analysis Diagram" (fig. 3) leads to the following conclusions:

- the tests of large specimens with surface defects carried out at +20 °C have shown that practically in all cases of base material testing some subcritical crack growth occurred before final brittle (semi-brittle) failure started, its size has a reciprocal dependence of defect size, with the rate of growth being proportional to the testing temperature;

- comparison of experimental results with calculation based on linear elastic fracture mechanics suggests a high conservatism of calculations, especially for materials with surface defects smaller than 30 mm in depth when initiation of subcritical crack growth started at yield strength and the subsequent failure occurs at ultimate tensile strength of materials (fig. 4).

- subcritical crack growth started at the whole crack front, the largest values being observed for the highest values of stress intensity factors of the crack;

- detection of the initiation of subcritical crack growth was measured by acoustic emission and electrical potential drop (alternating current) methods. Both methods give relatively comparable results for this case of tests, even if acoustic emission method signalled lower stress values than the electrical potential one;

- the geometrical size factor is produced even for fully brittle fractures: reduction in specimen size with defect initiates a certain transition temperature shift in fracture stresses to lower temperatures, for example the reduction in scale 1:8 represents a temperature shift equal to -150 °C;

- linear elastic fracture mechanics (LEFM) can be applied only to stresses up to cca 0.75 of yield strength of the material (even if plane strain conditions are met), failure conditions for higher stresses are controlled by classical strength theory when failure stress R_f(brutto) depends on netto-section, and netto-failure stress is approximately constant and equal to ultimate tensile strength of the material;

- conditions of brittle or quasi-brittle failure are very far in temperature scale from the crack arrest temperature as has been received for this type of steel by the ESSO type tests. Even for specimens 150 mm thick this crack arrest temperature is shifted (for similar nominal stresses) by +50 °C higher than temperature dependence of failure stress for specimens with 100 mm deep defects;

- the tests of large specimens with surface defects in the weld metal of electroslag or submerged arc weldments show that failure mode is determined by test temperature and defect size. In cases of deep defects (75 mm or more) its failure mode is brittle at room temperature; if defect size is reduced to 15 mm then failure mode at room temperature is changed into a semi-brittle one with large subcritical crack growth;

- the comparison of results from tests of specimens from base material and welding joints show that temperature dependencies of fracture stresses for weldments are shifted to higher temperatures, these temperature shifts are close to the differences between transition temperatures of both materials: by this way the "brittleness critical temperature" has been approved;

- the Defect Analysis Diagram (fig. 4) permits to evaluate with a high conservatism the safety condition of a structure with defects and also to evaluate the allowability of such defects.

THE STRESS CONCENTRATOR TESTS

Strain processes in areas with stress concentrators have decisive influence on complex structural element lifetime. Part of our experimental program of large scale model tests has been aimed at experimental verification of formulae for local strain calculations used in Codes for nuclear reactor pressure vessels.

Experimental results

Four models of pressure vessel nozzles of ID 850 mm in scale 1:3 have been tested in testing equipment ZZ 8000 by pulsating loading in tension (coefficient of cycle load assymetry R = 0): the first model by maximum loading equal to 36 MN, three others up to 20 MN. The models (plates 800 mm wide and 100 mm thick with nozzles of ID equal to 280 mm) have been machined from 15Kh2NMFA type of steel with properties shown in table 2. Theoretical (Hook´s) stress concentration coefficients have been calculated from measured strains (in 28 points along nozzle radius) and from nominal strain. Values between 2 and 3.9 have been obtained.

Calculation of local elastic-plastic strain field

Generally, the following expression can be written for the coefficients of concentration:

$$\alpha_\sigma \leq \alpha_H \leq \alpha_\varepsilon \qquad (2)$$

where $\alpha_\sigma = \frac{\sigma_{max}}{\sigma_n}$ - stress concentration coefficient,

$\alpha_\varepsilon = \frac{\varepsilon_{max}}{\varepsilon_n}$ - strain concentration coefficient,

α_H - theoretical (Hook´s) stress concentration coefficient,

σ_n, ε_n - nominal values of stress and strain, respectively.

Hardrath and Ohmen (1953) used the following empirical formulae:

$$\alpha_\sigma = 1 + (\alpha_H - 1)\frac{\alpha_\sigma}{\alpha_\varepsilon} \tag{3}$$

and

$$\alpha_H = \alpha_\varepsilon \tag{4}$$

These expressions have been adapted by ASME Boiler and Pressure Vessel Code, Section III, Division 1.

Neuber (1961) received for stresses and strains near a parabolic notch the relation as follows:

$$\alpha_\sigma \cdot \alpha_\varepsilon = \alpha_H^2 \tag{5}$$

This method is used in Soviet Standard for Strength Calculation of Elements of Reactors, Pressure Vessels and Piping of Nuclear Reactors and Power Stations (1973).

A method based on a generalized principle of equivalent energy was published by Glinka (1983) and Polák (1984). This method proceeded from the independence of strain energy density in concentrator notch with respect to the shape of stress-strain diagram of the material. For elastic and elastic-plastic region of loading it can be written

$$W_{max} = \alpha_H^2 \cdot W_n \tag{6}$$

where

$$W_n = \int_0^{\varepsilon_n} F(\sigma)\, d\varepsilon \tag{7}$$

where W_n - strain energy in places loaded by nominal stresses only,

W_{max} - strain energy in place of stress concentrator.

All described methods can be used for calculating the local stresses and strains for materials with arbitrary stress-strain diagram; the following comparison is made with the suggestion of similar shape of stress-strain diagram in tension and compression.

Comparison of experiments with calculations

Fig. 5 shows a comparison of local strains calculated by the preceding methods, with experimental values for nominal stress 310 MPa; the values of strain are shown as dependent on the theoretical (Hook's) stress concentration coefficient. For this case also for other stress levels Neuber relation (5) best fits for the whole region of α_H. Measured residual local strains at the end of the first cycle (for $\sigma_n = 0$) are substantially higher than the calculated ones; again, Neuber relation (5) gives the best fitting results.

From graphic interpretation it follows that the measured dependence $\varepsilon = f(\alpha_H)$ is of linear type for both cases. This line of total strain for stabilized material after repeated loading by $\sigma_n = 0.55\ R_p0.2$ is, on the contrary, best represented by Hardrath and Ohman relation (3), which is recommended by ASME Code, Section III.

THE CRACK GROWTH TESTS

Tests and calculations of crack growth rates for standard and/or complex loading conditions during repeated loading in elastic region are practically fully understood and known. More complicated are cases where cracks are cyclically loaded in elastic-plastic regions, especially in stress (strain) gradient fields as can be represented by nozzles of real structures such as pressure vessels.

Thus, the same type of aforementioned models has been used for the measurement of crack growth rate. Quarter-circular artificial crack-type defects have been situated into nozzle radius; their initial depths have been equal to 15, 30 and 45 mm. Each model contained only one crack and was loaded by 1,200 cycles up to maximum load equal to $\sigma_n = 519$ MPa (for this load the maximum local strain in nozzle radius is twice higher than for the overpressure test; the total number of cycles is 10-times larger than the designed number for the whole reactor lifetime).

The crack growth rates during repeated loading have been analysed by the following two approaches:

- the elastic fracture mechanics using elastic (Hook's) stress intensity factors K_I defined as follows:

$$K_I^x = M \cdot \sigma^x \cdot (\pi \cdot a)^{1/2} \tag{8}$$

where

$$\sigma^x = E \cdot \varepsilon \tag{9}$$

and standard Paris-Erdogan type law:

$$\frac{da}{dN} = C \cdot (\Delta K^x)^n \tag{10}$$

- the elastic-plastic fracture mechanics using the expression as follows:

$$\frac{da}{dN} = C_p \left[\Delta e_{pl} \cdot a^{1/2}\right]^m \tag{11}$$

where Δe_{pl} - local plastic strain in nozzle radius (i.e. in stress concentrator).

The results of this analysis are shown in fig. 6. For both cases, even for a small set of results, a good agreement with both expressions (10) and (11) may be seen. Values of crack growth rate above 10^{-5} m.cycle^{-1} have been received.

CONCLUSIONS

This report tries to demonstrate a part of a wide experimental program aimed at analysing the WWER reactor pressure vessel safety and lifetime, as well as the conservatism of present reactor pressure vessel codes.

The results and the following analysis have shown the necessity and the advantages of testing large scale specimens and/or structural element models, as for example nozzles, in both static and cyclic loading regimes.

In static tests the existence of the geometrical size effect in brittle/semibrittle mode of failure has been demonstrated and also the correctness and applicability of linear elastic fracture mechanics approach has been discussed.

Tests of nozzle models (with stress concentrators) allow to compare different calculation methods and to choose the best one.

Measurement of crack growth rate in elastic-plastic region of loading in stress/strain gradient field (nozzle radius) have been also discussed and compared with empirical formulae.

Generally, testing of large scale models and specimens are still necessary and in some cases only they can give the definite word to reactor pressure vessel safety evaluation.

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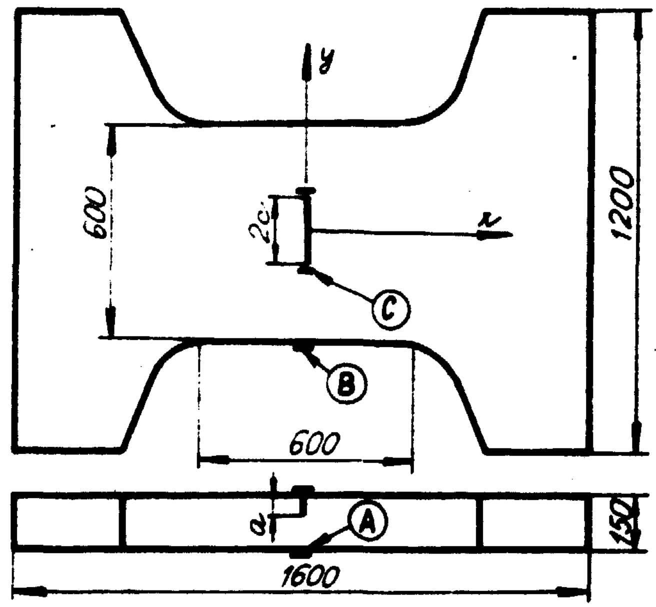

Fig. 1. Large scale testing specimen for testing in ZZ 8000

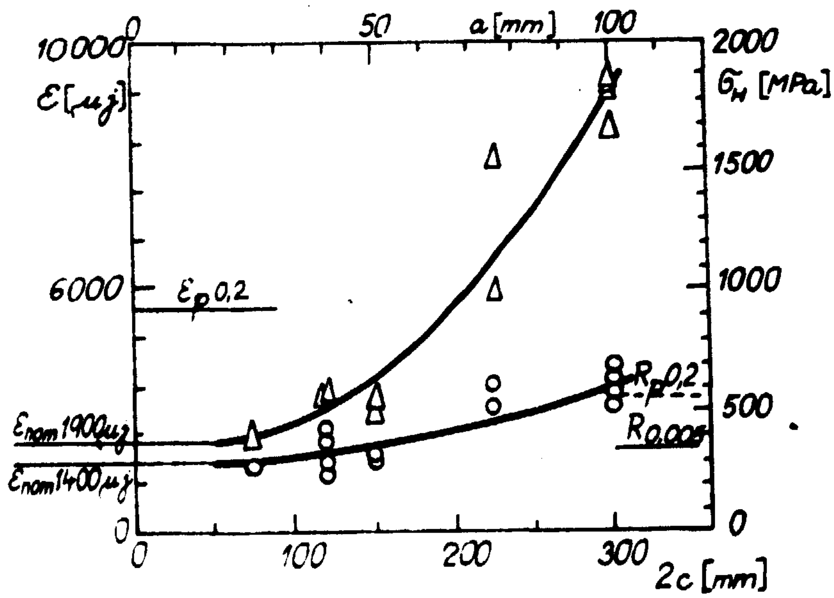

Fig. 2. Dependance of strain values on distance from crack tip

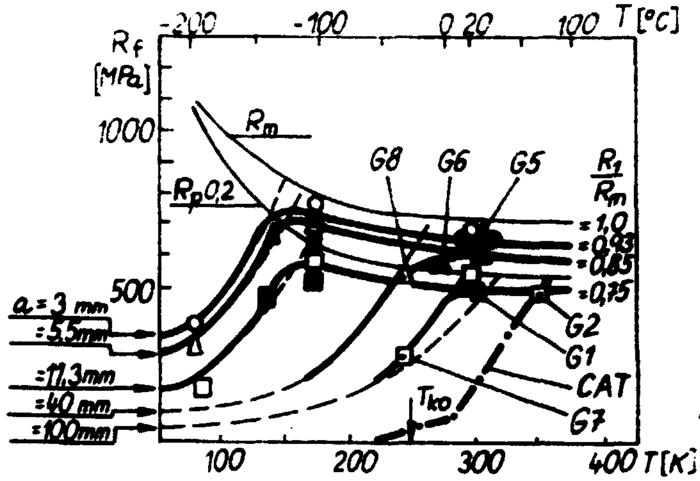

Fig. 3. Fracture Analysis Diagram of 15Kh2MFA type steel

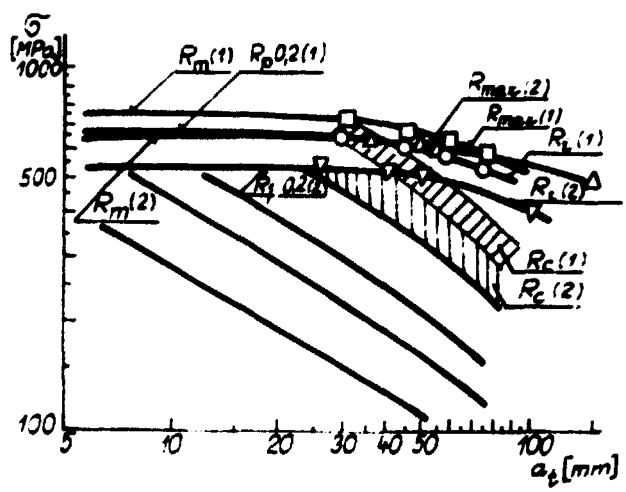

Fig. 4. Defect Analysis Diagram of 15Kh2NMFA (1) and 15Kh2MFA (2) steels of thickness 150 mm at + 20 °C
R_c - calculated critical stress according to LEFM and values K_{IC} according to Table. 2

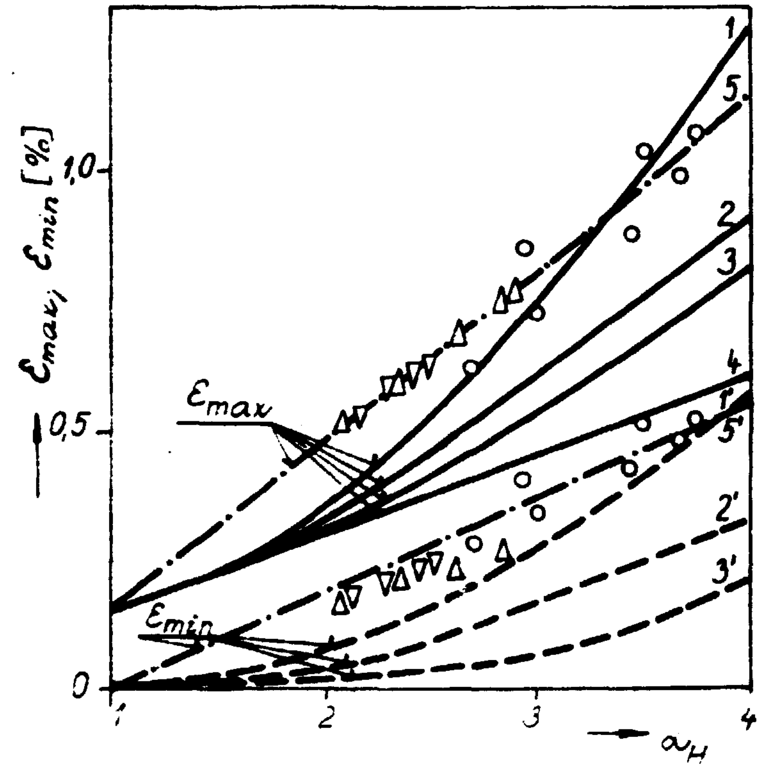

Fig. 5. Local strain in nozzle radius in dependance on α_H for nominal stress equal to 310 MPa

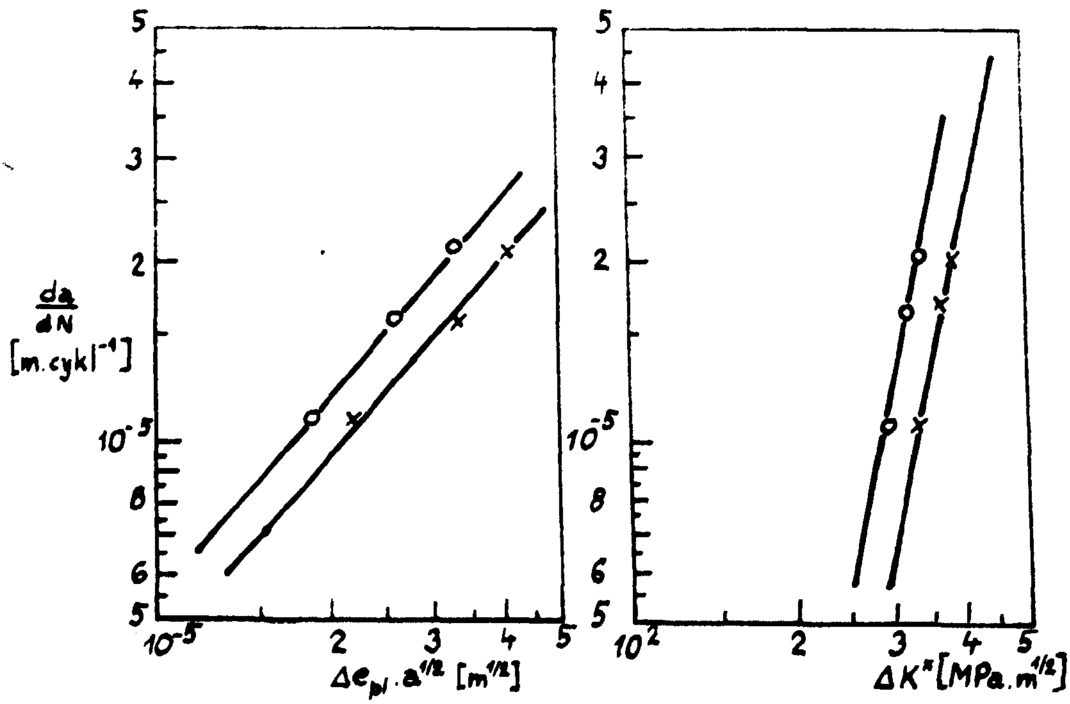

Fig. 6. Crack growth rate in 15Kh2NMFA type steel in nozzle radius after elastic-plastic loading