Analysis of the Conditions of Brittle Failure of WWER Type of Reactor Pressure Vessels on the Basis of Large Scale Specimen Testing

BRUMOVSKÝ M., POLACHOVÁ H.
SKODA Concern, Plzen, CSFR
ANIKOVSKIY V., DRAGUNOV Yu., RIVKIN E.
OKB Gidropress, Podolsk, USSR
FEDOSOV A.
CNIITMASh, Moscow, USSR

ABSTRACT

An experimental verification of conditions for brittle fracture initiation calculations for WWER reactor pressure vessels byl large scale model testing was performed. Results have been compared with Linear Elastic Fracture Mechanics as well as with R6, Rev.3 models.

1 INTRODUCTION

One of the most important tasks with respect to ensuring reactor pressure vessel (RPV) safe operation is to eliminate any possibility of fast (brittle or semi-brittle) fracture. Codes that are used nowadays, are based on Linear Elastic Fracture Mechanics (LEFM) for cases of nuclear reactors. This approach is very conservative, especially in the area of elastic-plastic loading that are important for RPVs in cases of emergency cooling. Moreover, operating conditions (high temperatures) as well as used steels of medium strength cause that necessary conditions of plane strain are not fulfilled even for high thicknesses of RPV walls; thus LEFM approach can be exchanged by another approach that takes these conditions into account - one of the most realistic is the R6, Rev.3 one.

Tests of large scale specimens of real thickness equal to RPV wall are very useful to determine real conditions of fast fracture initiation. If they have surface semielliptical defects, their results can be compared with calculated parameters received directly from Codes.

During last several years coordinated research programme has been carried out in ŠKODA Concern, Plzeň, ČSFR together in cooperation with OKB "Gidropress", Podolsk and CNIITMASh, Moscow, both from USSR.

2 MATERIALS AND TESTING PROCEDURES

Large scale specimens were manufactured from plates of 150 mm thick from materials used for WWER 440 and WWER 1,000 MW units i.e. from steels (BM) of 15Kh2MFA and 15Kh2NMFA types as well

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as from their welding joints - electroslag (ES) and submerged arc welds (A/S). Main characteristics of these materials are given in Tables 1 and 2.

Table 1. Chemical Composition of Materials [mass %]

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
15Kh2NMFA steel	0.13	0.41	0.23	0.010	0.018	2.06	1.32	0.63	0.07

Table 2. Mechanical Properties of Materials at 20 °C

material	$R_p0.2$ [MPa]	R_m [MPa]	A_5 [%]	Z [%]	KCV [$J.cm^{-2}$]	T_{ko}^{x} [°C]	K_{IC} [$MPa.m^{0.5}$]
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	+40	80
15Kh2NMFA Steel	570	660	21.4	70.0	200	-30	220÷250
S/A Weld Metal	500	610	21.0	64.0	85		180
ES Weld Metal	650	750	18.5	71.0			135

ˣTransition temperature T_{ko} is defined as follows in principle
-at temperature T_{ko} 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 temperature equal to T_{ko} + 30 °C mean value of KCV from three tests must not be lower than 90 $J.cm^{-2}$ and mean value of shear fracture appearance must be larger than 50 %.
This transition temperature lies within an interval of RT_{NDT} ± 10 °C, as was demonstrated for both type of steels.

Large scale tensile flat specimens with testing section of 150 x 600 mm with different surface semielliptical crack-type defects were tested on testing equipment ZZ 8000 of maximum tensile force of 80 MN; tests have been carried out in temperature range of T_{ko} ± 50 °C. Conditions of fast fracture as well as of subcritical crack growth initiation were fixed by measuring the following parameters : force, temperature, crack opening displacement, extension, strain field, acoustic emmission and electrical potential drop.

3 RESULTS AND THEIR DICUSSION

Results from testing of 15Kh2MFA type of materials are shown in Figure 1. In this figure plain curves represent mean values of fracture toughness determined from tested materials by standard fracture specimens, dashed line represents the design fracture toughness curve according to the USSR Code [1]. Experimental points show to the fact, that, in most cases, an initiation of subcritical crack growth starts closely to the mean value curves. In the case of submerged ard weld, their initiation is observed at values lower than mean curve, in general, as weld metal is very nonhomogenous and the initiation starts at the weakest point bead but practically in all cases at values beyond the design curve [1].

Figures 2 and 3 summarize results from the same steel but in dependence of critical netto-stress vs. crack depth. Figure 2 for base metal as well as Figure 3 for weld metals show the

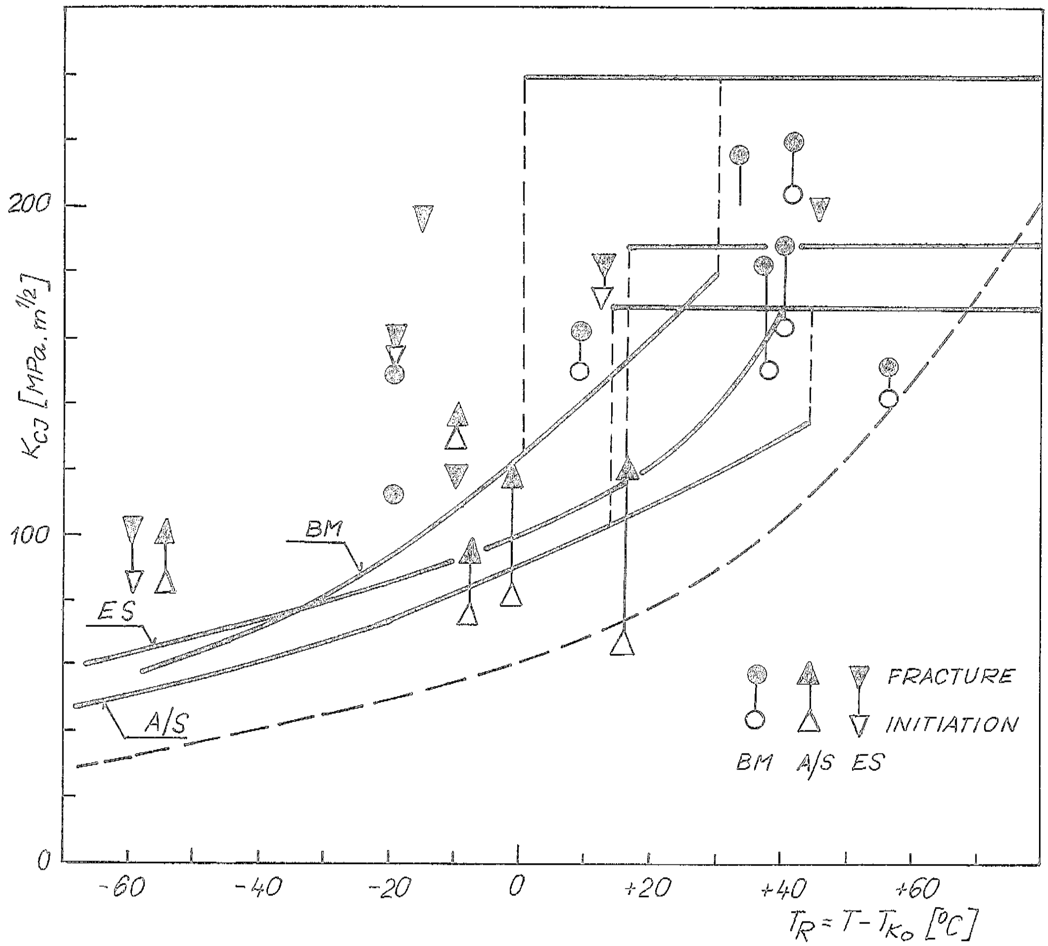

Fig.1. Results of testing of 15Kh2MFA type of steel

fact that initiation netto-stresses are practically equal to the yield strength of materials, while fracture netto-stresses are practically equal to the ultimate tensile strength of tested materials at all tested temperatures over the critical temperature T_{ko}. An effect of crack on these stresses is observed only for temperatures belowe T_{ko}, i.e. the LEFM approach can be used only for this region.

Similar results are shown in Figure 4 for specimens from 15Kh2NMFA type of steel and its welding joints. All tests were performed, in this case, at room temperature, i.e. with relatively high fracture toughness values (see Table 2). Some effect of crack size on critical stresses is seen only for electroslag weldment, i.e. for material with the lowest fracture toughness values. In all cases, for both types of steels, some effect of crack size on critical netto-stresses can be observed for conditions with lower fracture toughness of material, as well as for crack crack sizes larger than 40 mm in depth.

Thus, it was demonstrated that use of LEFM even for thick walled RPV is very conservative, especially in cases when the design fracture toughness curve according to Nuclear Codes is used. Safety coefficients for these situations are much higher than it would be usable. From this reason, comparison with R6, Rev.3 curve was performed. This design curve is given as [2]:

$$K_R = [1 - 0.14\ L_R^2][0.3 + 0.7\ \exp(-0.65\ L_R^6)]$$

where

$$K_R = \frac{K_I}{K_{IC}}, \text{ and } \quad L_R = \frac{\sigma}{R_p}$$

In Figure 5 all results received for both types of steels and their welding joints are summarized. For calculations only mean real fracture toughness values of tested materials (see Table 2) have been applied, as well as mean yield strength values. Relatively good correlation of experimental points and

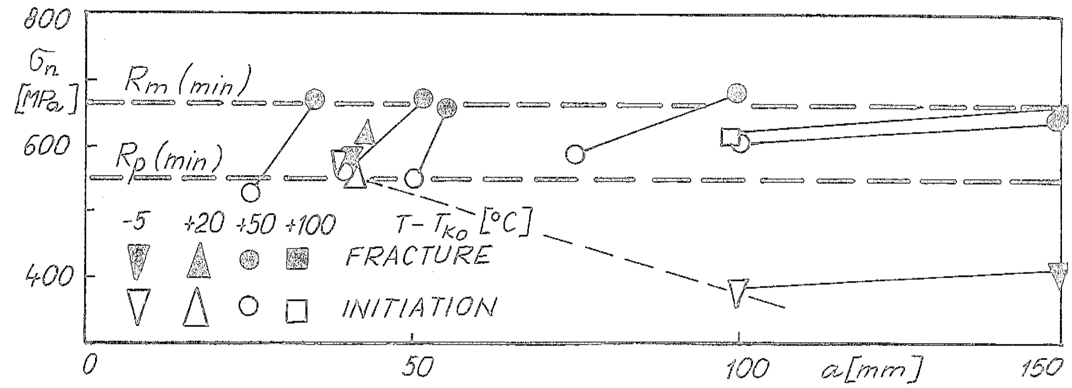

Fig.2. Results of testing of 15Kh2MFA type of steel a/2c=1/3

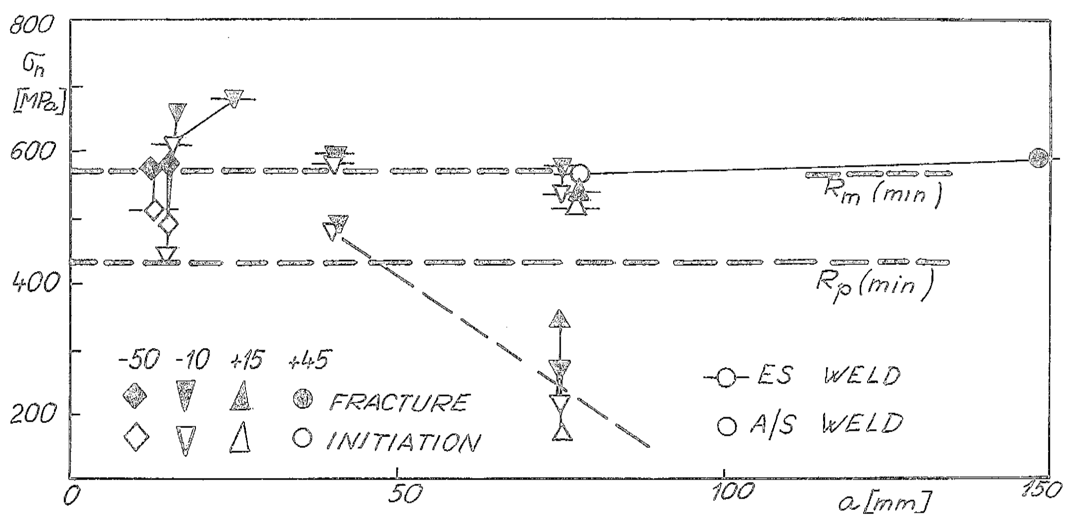

Fig.3. Results of testing of welding joints of 15Kh2MFA type of steel a/2c= 1/3

design curve has been established - practically in all cases the initiation points are close to the design curve. Safety factors, determined with respect to stress intensity factors K_I or with respect to stress lie in interval between one and two. Of course, if design fracture toughness values would be used, then all results would lie substantially higher than the R6 design curve and safety factors would be at least twice larger, i.e. safety would be fully reliable.

4 CONCLUSIONS

Research programme on large scale specimens from WWER RPV materials shows some important facts :

/1/ testing of these specimens gives very useful and important informations from the point of view of verification of Code calculation method and their application to the RPV design;

/2/ calculation Codes (USSR, CMEA, and ASME) based on LEFM approach are sufficiently conservative and ensure reliable operation of WWER reactors;

/3/ design curve from the R6,Rev3 approach gives better consent with experimental results.

REFERENCES

[1] USSR Standards for Strength Calculations of Components and Piping of Nuclear Power Plants (1989) , Moscow

[2] Milne,I., Ainsworth,E.A., Dowling,A.R., Stewart, A.T. Assessment of the Integrity of Structures Containing Defects; CEGB Report R/H/R6-Revision 3 (1986)

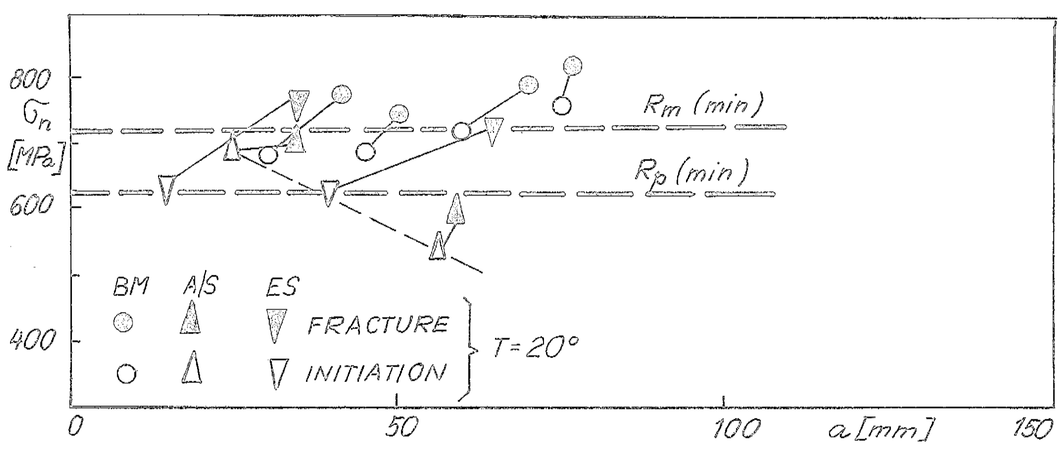

Fig.4. Results of tests of 15Kh2NMFA type of steel and its welding joints at room temperature a/2c = 1/5

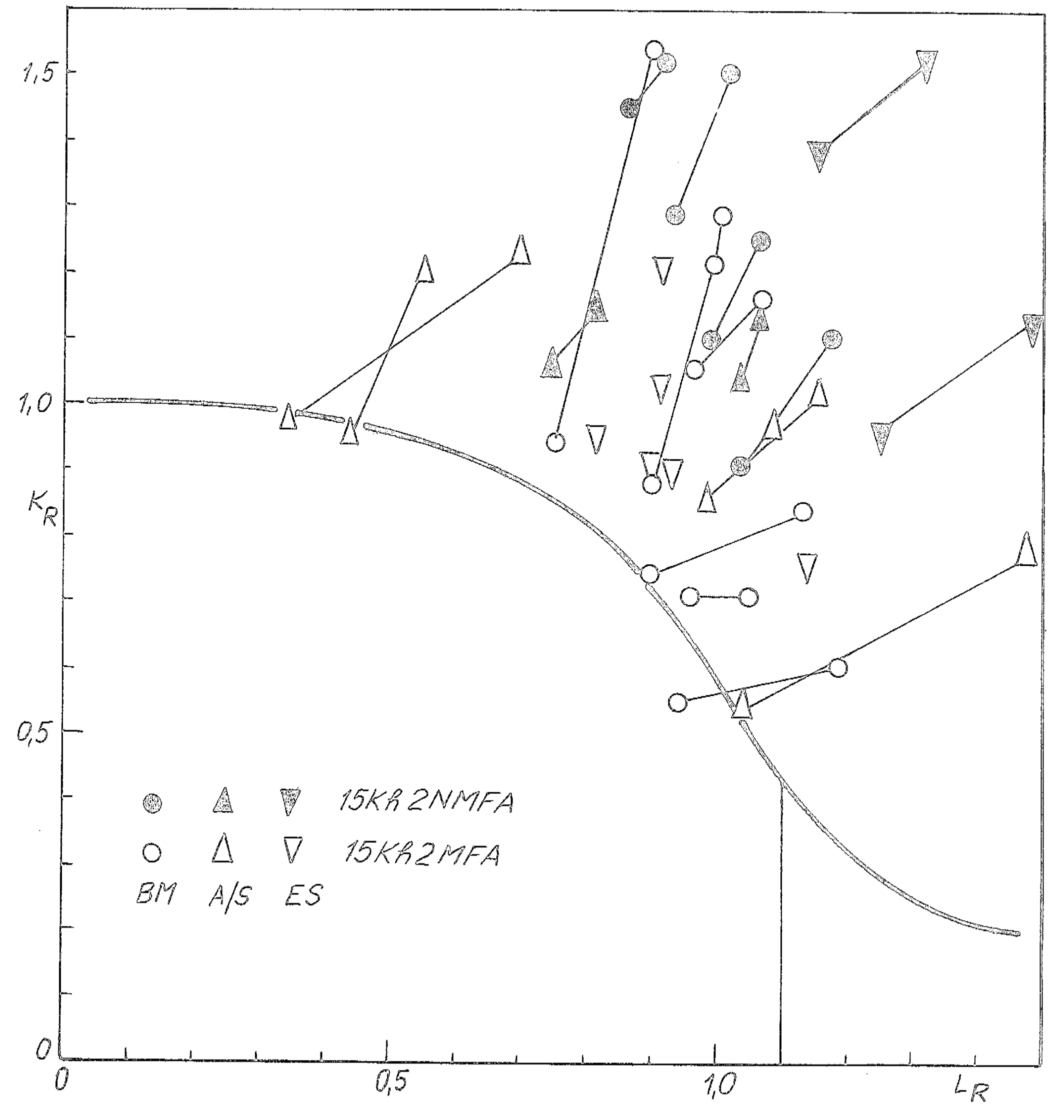

Fig.5. Summerization of all experimental results with the design curve according to the R6,Rev.3 model