Investigations to Size Effects on Plastic Deformation and Failure Behavior of Inhomogeneously Loaded Structures

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ABSTRACT

Starting investigations to size effects on deformation and failure behavior of inhomogeneously loaded structures tensile test series at room temperature with specimens of similar geometry and different sizes are performed. The specimens, cut from the wall of a real reactor vessel, are flat and include a central hole in order to obtain inhomogeneous deformation with high strain gradients, which will be higher in the smaller specimens and might be responsible for size effects.

In this paper, the preliminary results of the tests are presented. The size effects in the global and local mechanical behavior are discussed.

INTRODUCTION

The knowledge of local admissible strains of reactor vessel components is very important for design evaluations as well as for the integrity check of the reactor pressure vessel after severe accident loads. Usually failure strain is determined on quasi homogeneously loaded labor specimens and is applied to inhomogeneously loaded structures using an appropriate multiaxial criteria. Thereby the difference in size between labor specimens and large structures like the reactor vessel is neglected. In advanced deformation theories, developed and discussed extensively in the nineties, size effects on the deformation behavior are expected in the case where inhomogeneous loading leading to deformation with high gradient is present [1,2]. Indeed few – questionable - experiments could indicate such size effects [2]. In contradiction size effects on the damage behavior are more recognized and in the fracture mechanics a well known fact.

In the European research project LISSAC (Limit Strains for Severe Accident Conditions) the size influence on material properties, e.g. failure strain, needed for the best possible assessment of components failure due to severe accident is investigated [3]. Within our activities in LISSAC, tensile test series at room temperature with specimens of similar geometry and different sizes, cut from the wall of a real reactor vessel are performed. We started our investigations with flat specimens include a central hole. The hole is incorporated to obtain inhomogeneous deformation with high strain gradients, which will be higher in the smaller specimens and might be responsible for size effects. To collect a lot of information about deformations in the hole surrounding area appropriate measuring techniques are used.

In the following the experimental procedures and the measuring techniques utilized are explained. Thereafter first results are presented and discussed.

EXPERIMENTAL PROCEDURES

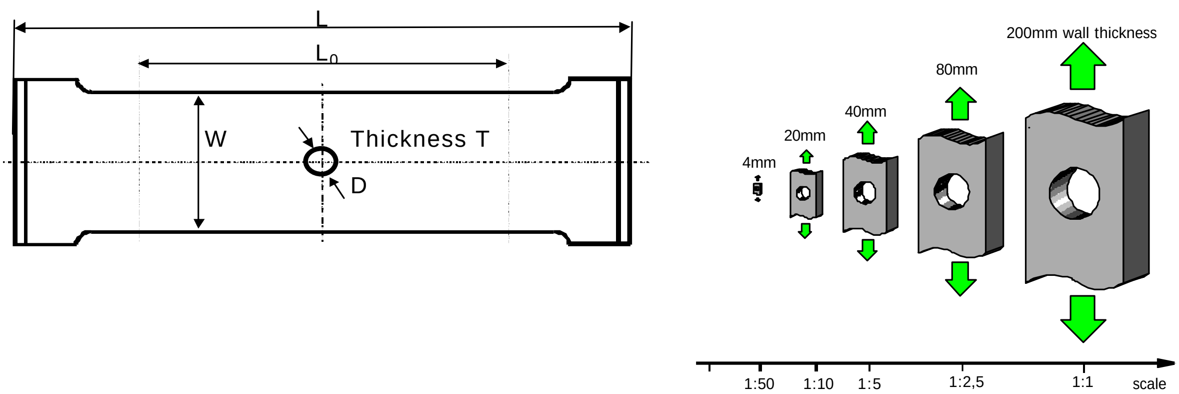
The material used (22 NiMoCr 3 7) was cut from the wall of a reactor vessel, foreseen for BIBLIS C, which is a nuclear power plant in Germany. The steel was manufactured by the Japan Steel Company. It is similar to A 508 CI 2 material. The chemical composition is given in Table 1.

Table 1. Chemical composition of the cylindrical shell from Reactor Pressure Vessel BIBLIS C, Material 22 NiMoCr 3 7 similar to A 508 Cl 2 according to Test Certificate TÜV Bayern, Test-No.: 141 5113/6

Check Analysis[1)]	Constituents														
	C	Si	Mn	P	S	Ni	Cr	Cu	Mo	V	Ta	Co	Al	Sn	As	Sb
Specification	.17/ .25	.10/ .35	.50/ 1.00	max. .012	max. .015	.60/ 1.00	.25/ .50	max. .10	.50/ .75	max. .050	max. .030	max. .030	max. .050	-	-	-
maximum	.25	.20	.95	.008	.009	.091	.42	.04	.59	<.01	<.005	.011	.027	.010	.011	.002
minimum	.18	.17	.84	.006	.005	.083	.39	.03	.51	<.01	<.005	.010	.017	.005	.007	.001
average	.22	.19	.89	.007	.007	.87	.40	.04	.55	<.01	<.005	.011	.019	.008	.009	.001

1) from 33 specimens

Among others flat tensile specimens with a center hole were fabricated according the geometry illustrated in Fig. 1. Thereby specimens of different sizes scaled from 1:1 down to 1:50 were foreseen (Fig.1). The main dimensions of the scaled specimens are given in the table enclosed to Fig 1.



Specimen ID	Dimensions in mm				
	T	W	D	L_o	L
1C	4	10	2	24	190
AL1	20	50	10	120	200
AJ1	40	100	20	240	400
AC1	80	200	40	480	800
AP	200	500	100	1200	2000

Fig. 1 Main dimensions and scale factors of specimens with center hole

The smaller specimens, 4 and 20 mm thickness, are tested at Forschungszentrum Karlsruhe (FZK) whereas the bigger ones at Staatliche Materialprüfungsanstalt (MPA). For the experiments at FZK servo-hydraulic testing machines are used with a capacity of 160 and 630 kN, respectively. At the MPA, testing machines with capacities up to 100 MN can be applied.

For measuring inhomogeneous three-dimensional deformations and therewith the strain gradients during the tensile loading up to failure, an optical system was used at FZK which works on the basis of the “Object Grating Method“ [4]. The method needs the preparation of the specimens with either a regular (deterministic) or a random (stochastic) pattern. For the preparation with a stochastic pattern the specimen surface is sprayed by an antireflection white colored ground paint and in a second step by a black colored paint producing a random speckles pattern on the ground coat (s. Fig. 2). During test the specimen is viewed by two CCD-cameras whereas the two cameras - instead of one camera - are necessary to determine the out of plane – in addition to the in plane – displacements (3D-measurment).
Starting the test, the pattern on the surface will be deformed along with the specimen. The deformation of this pattern under increasing load is recorded by the cameras shoots triggered suitably and evaluated after test using digital image processing and resulting the 3-d-displacements and therewith the strains as well as the contour of the specimen.

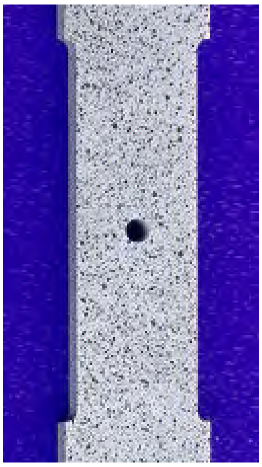


Fig. 2 Surface of prepared specimen

At the MPA another technique is applied to determine the surface deformations in the hole surrounding areas. After painting the surface with a black colored finish a deterministic pattern is scribed (s. Fig. 7), which is photographed with a video camera during the test. In addition the hole opening in the tensile direction is measured by a clip gauge. Strain gauges sticked in proper positions provide particular values in the stage of small deformations.

In all tests the global deformation of the specimens is monitored by an axial extensometer mounted at the test begin over the gauge length L_0. In order to determine the onset of local failure corresponding to macro crack initiation, the electric potential method is used. The tests are performed with a constant strain rate of 10^{-3} 1/sec (velocity of cross head divided by gauge length L_0).

RESULTS AND DISCUSSION

Meanwhile the tests with 4, 20, 40 and 80 mm thick specimens were performed. In a first comparison the measured nominal stress (force divided by the initial minimal cross section area) versus the global strain measured by the axial extensometer (elongation divided by the gauge length L_0) is plotted for the four scaled specimens in Fig 3. The curves show up to maximum load no distinctive difference and therewith no size effects on the global deformation behavior. The specimens pronounced yield points for the weakened and the full section could be detected. The yield and the maximum stress in the weakened sections of the 20 and 40 mm thick specimens exceeded slightly the values of standardized material tests (0.2-YS ≈ 440 MPa, UTS ≈ 600 MPa). After exceeding the elongation before reduction, a sharper drop in loading was found out caused by crack initiation and stable crack growth partly up to final separation depending on the stiffness of the tensile testing machine.

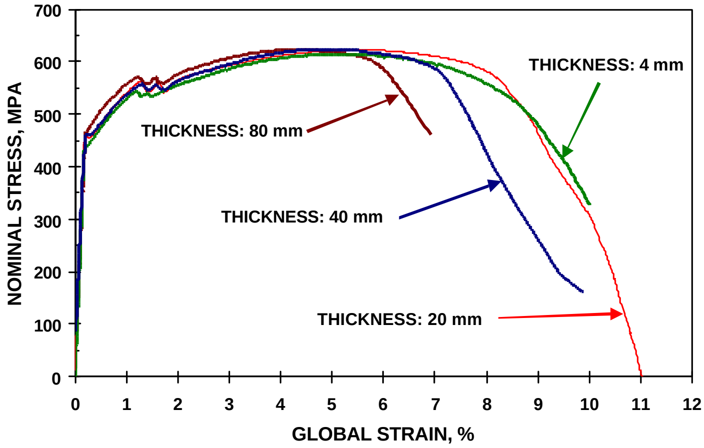


Fig. 3 Nominal stress vs. global strain for the different sized specimens in comparison

As far as nominal stress versus hole opening displacement - as a representative integral strain measure for the local deformation field surrounding the hole – is considered, differences could be recognized even between the 4 and 20 mm thick specimens (s. Fig. 4). The curves show in the decreasing path a remarkable drop or discontinuity in the first derivative. The position of this discontinuity might be identified by the state of macro crack nucleation and local failure, respectively. According this criterion a failure strain of 75, 61 and 48 % (denoted by filled circles) can be determined for the 4, 20 and 80 mm thick specimens, respectively. Unfortunately, due to exceeding the measuring range at approx. 60 % with the 40 mm thick specimen there is a loss of information at the largest specimen concerning the size effect. However following the criterion mentioned above the failure strain for the 40 mm thick specimen seems to be at least 60 %. Since the crack initiation is accompanied by cross section reduction due to plastic deformation the potential drop method did not provide us useful information concerning the time of macro crack initiation.

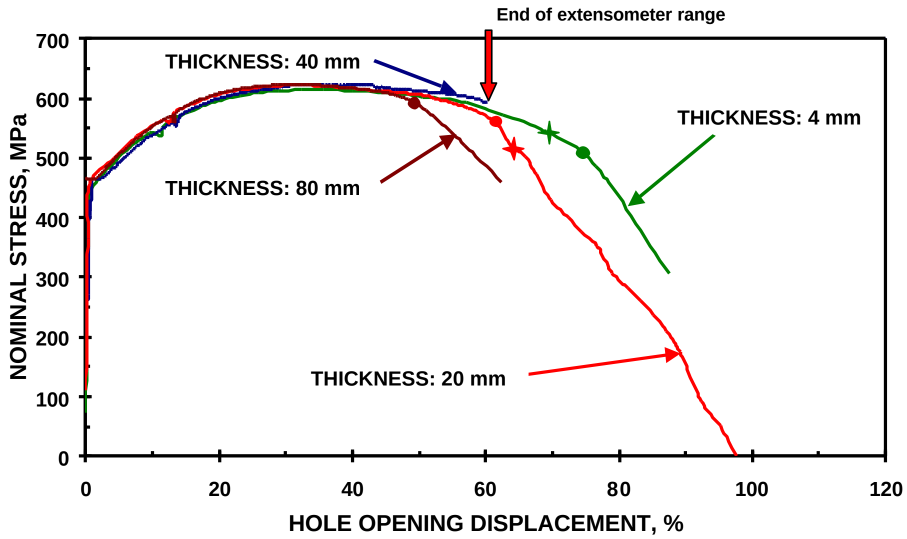


Fig. 4 Nominal stress vs. hole opening displacement for the different sized specimens in comparison

The hole opening displacement is an integral value and accordingly the failure strains determined above are less than the local failure strains appearing where the macro crack nucleate. Having a closer look to the fracture surfaces of the specimens (s. Fig. 5) the position of macro crack nucleation seems to be inside the specimen at the smallest cross section.

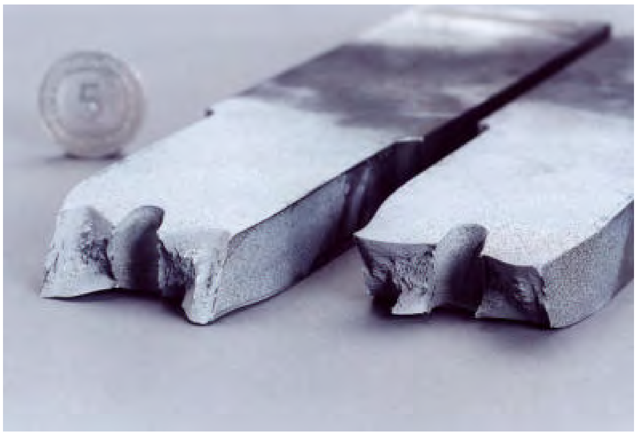


Fig. 5 Fracture surfaces of the 20 mm thick specimen

The strain at that position can not measured. However this strain is higher than the maximum local surface strain measured monitoring the surface of the specimen, which might be a better estimation – less conservative - than the hole opening displacement. In Figs. 6a and 6b distributions of the axial surface strain component measured at the time of macro crack initiation for the 4 and 20 mm thick specimens, respectively, are plotted. From this distributions maximum values of 88 and 73 % can be determined for the 4 and 20 mm thick specimens, respectively. Since the video shoots of the 40 and 80 mm thick specimen have not yet been evaluated, similar results are not available.

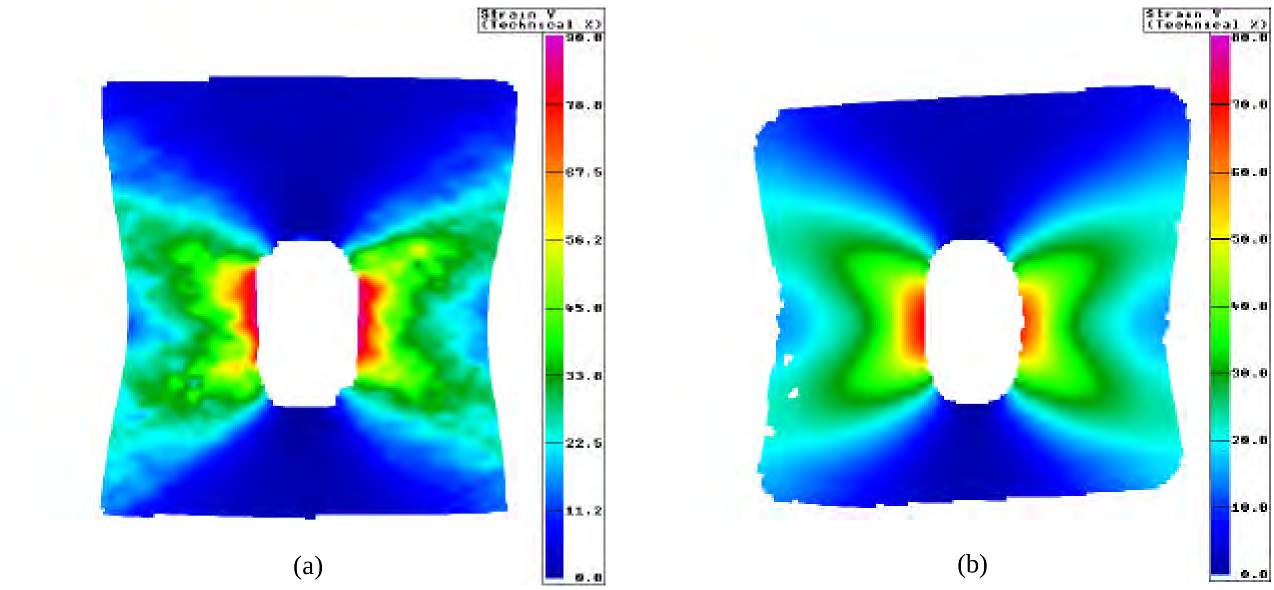


Fig. 6 Measured distribution of the axial surface strain component for the 4 mm (a) and 20 mm (b) thick specimen, respectively, at the time of macro crack nucleation

Another criterion to identify the deformation state of macro crack nucleation suggested for tensile tests with round bar with circumferential notch was also considered [3]. Accordingly the hole opening displacement at the time of macro crack nucleation is determined using the broken pieces of the specimen by putting them as close as possible and measuring the axial hole diameter and the crack opening (s. Fig. 7). Subtracting the crack opening from the value of the axial hole diameter gives the hole opening at the time of local failure. When applying this criterion to our specimens, hole opening displacements of 69 and 64 % are determined for the 4 and 20 mm thick specimens (denoted by crosses in Fig. 4). These values differ slightly from those determined by the criterion of curve drop considered above.

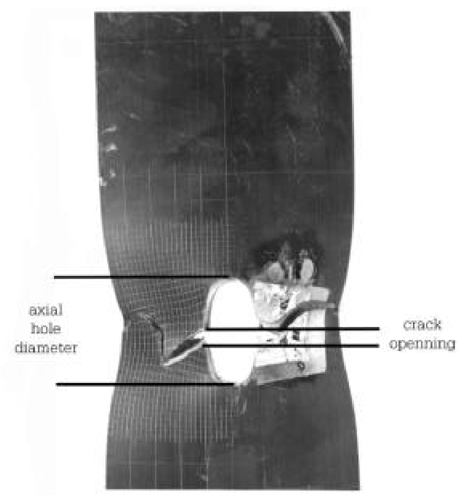


Fig. 7 Specimen after final cracking

CONCLUSIONS

As preliminary results all specimens failed after considerable deformations by tough forced ruptures with high shear fracture portions in the fracture plane (Fig. 5). A size effect on the deformation behavior could not ascertain with the present investigations based exclusively on a thickness of 4, 20, 40 and 80 mm. A size effect on the damage behavior could be recognized which was hardly possible for the smaller specimens without the deformation field measurements performed. On the base of proper criteria the size influence on failure strain is quantified: The bigger the size the lower is the failure strain. Within the size range investigated a relative reduction in failure strain of approximately 36 % could be identified. Further investigations extending the size range will provide reliable and less conservative values applicable to large structures like the reactor vessel of a PWR.

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REFERENCES

[1] Aifantis, E. C., “Gradient effects at macro, micro, and nano scales,” J. Mech. Behavior of Materials, vol. 5, pp. 355-375, 1994

[2] Fleck, N. A., Muller, G. M., Ashby, M. F. and Hutchinson, J. W., “Strain gradient effects in plasticity: Theory and experiment,” Acta Metall. Mater., vol. 42, no. 2, pp. 475-487, 1994

[3] Krieg et al., “Limit Strains for severe accident conditions. Description of an European Research Program and first Results,” August 2001,Washington. To be published in: Transactions of the 16th International Conference on Structural Mechanics in Reactor Technology.

[4] Erbe, M., Galanulis, K., Ritter, R. and Steck, E., “Theoretical and experimental investigations of fracture by finite element and grating methods,” Engineering Fracture Mechanics, vol. 48, no. 1, pp. 103-118, 1994