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Analysis of WWER 1000 SG Cold Collector Cracking

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Introduction

In 1986 steam generator cold collector cracking was first detected at WWER 1000 units made and operated in the former Soviet Union. The causes of collector cracking have been identified as environmentally assisted cracking of low alloy bainitic steel of type 10NiMo8.5 (10GN2MFA) in secondary side water environment at about 290°C. A lot of steam generators under operation have not shown this type of cracking, hence the plant specific operational practices and or manufacturing procedures to be related to its occurrence.

Investigations over the last 15 years have indicated that in bainitic low alloy steel/high temperature water environment systems subcritical crack growth is significantly affected by sulphur content, MnS inclusion type, shape and orientation, dissolved oxygen content, stress/time pattern and temperature [1]. Very long term operation at about 300°C could result in thermal ageing of 10NiMo8.5 (10GN2MFA) steel because of its higher content of Ni. Due to the plastic deformation of ligaments between holes in perforated area of collector strain ageing could occur in these regions during operation of steam generator.

As a result of recommendations summarized in the final report of consultants' meetings on „Steam Generator Collector Integrity of WWER 1000 Reactors“ held in Vienna in 1993 [2] large experimental program was started in VÍTKOVICE focused on:

1. A detailed study of strain and thermal ageing and dissolved oxygen content on subcritical crack growth in 10NiMo8.5 (10GN2MFA) steel.
2. A detailed study of the effect of high temperature water and tube expansion technology on fracture behaviour of ligaments between holes for heat exchange tubes.
3. A detailed study of the effect of drilling, tube expansion technology and heat treatment on residual stresses on the surface of holes for heat exchange tubes.

The aim of all these investigations was to find a dominant damage mechanism responsible for collector cracking to be able to judge the efficiency of implemented modifications and suggested countermeasures and to answer a very important question whether proper operation conditions (mainly water chemistry) make the operation of steam generators made in VÍTKOVICE safe throughout the planned lifetime.

Test material and experimental techniques

To study the effect of thermal and strain ageing and dissolved oxygen content on subcritical crack growth, the 53x12x290 mm bars were cut from a collector forging. Its chemical composition is shown in Tab. I.

Table I. Chemical composition of studied heat of 10NiMo8.5 steel (wt.%)

C	Mn	Si	Ni	Cr	Mo	V	P	S	Cu	Ti
0,11	0,97	0,24	1,97	0,21	0,46	0,03	0,009	0,007	0,072	0,005

One third of the bars was deformed in tension at a deformation rate of $\varepsilon_{at} = 1.10^{-3}s^{-1}$. When 5% plastic deformation was reached, the load was removed. Then the samples were aged for two hours at 250°C. The test specimens manufactured from the bars were oriented such that the crack propagation plane was perpendicular to the direction of plastic deformation. The second part of the bars was taken through a step cooling from 595 °C used to simulate long term service at operating temperature. Tensile properties of the studied structure states are summarized in Tab. II.

Table II. Summary of tensile properties at laboratory temperature.

	R_e [MPa]	$R_{p0,2}$ [MPa]	R_m [MPa]	A_5 [%]	Z [%]
as received condition	532		631	25,0	69
state after ageing 5% + 250 °C/2h		742	742	12,4	66
after step cooling	547		647	25,2	74

It is evident from tab. II that step cooling had no detrimental effect on tensile properties at laboratory temperature. However severe loss of impact toughness and shift of transition temperature was observed after this heat treatment, see Fig. 1. This is due to significant occurrence of intergranular fracture mode, attributed to segregation of impurity elements, in our case mainly P, to prior austenite grain boundaries [3].

To determine the effect of a tube expansion technology on a fracture behaviour of ligaments and to compare the effect of drilling and tube expansion technology on residual stresses on the holes surface the tubes were expanded into experimental blocks shown in Fig. 2a using both explosive and hydraulic expansion technology. Thickness of ligaments between adjacent holes has corresponded to that observed in a half of a collector wall thickness. Then the experimental blocks were cut, like schematically shown in Fig. 2a, and special C(T) specimens were manufactured (see Fig. 2b), and fatigue precracked in air. X-ray diffraction analysis was used to measure both axial and tangential residual stresses on holes surface.

Fracture mechanics tests in air were carried out at 290 °C on MTS 500kN servohydraulic testing machine in stroke control at a displacement rate of 0,5 mm/min.

Slow strain rate tests of C(T) specimens at 290 °C were performed at a displacement rate of 0,001 mm/min, to determine the effect of water environment on fracture behaviour. Both fatigue and fracture mechanics tests in high temperature water were performed on an INOVA servohydraulic testing machine fitted with an 111 litre static autoclave at two significantly different dissolved oxygen contents:

1. oxygen content corresponding at the beginning of the test to aerated or oxygenated water,
2. oxygen content corresponding to deaerated water.

Results and Discussion

Fracture behaviour of ligaments between holes for heat exchange tubes

To be able to judge the possibility of a catastrophic break of a collector in a quantitative manner the fracture behaviour of ligaments at operating temperature has to be known. For this reason fracture behaviour of ligaments was investigated in air at 290 °C. The aim of these experiments was to verify the effect of tube expansion technology on the fracture behaviour characteristics. As the characteristic feature of fracture behaviour of 10NiMo8.5 steel at temperatures from 20 °C to 320 °C was found to be a ductile stable crack growth the variation in J and δ with crack growth Δa (J-R, δ-R curves) was investigated using multiple specimen method [8]. Tests in air were carried out in a stroke control at the speed of 0,5 mm/min corresponding to the strain rate for dynamic strain ageing phenomenon [9].

Fig. 3 shows the J-R and δ-R curves obtained in air at 290°C. No effect of tube expansion technology was found. The values of $J_{0,1}$ and $\delta_{0,1}$ were expressed like stress intensity factors K_{CJ}, $K_{\delta C}$.

The calculated values of K_{CJ} and $K_{\delta C}$ are approximately the same like those obtained at laboratory temperature and at 250°C [10]. Therefore operating temperature of cold collector corresponds to the upper shelf region of fracture behaviour of 10NiMo8.5 steel.

The effect of dissolved oxygen on subcritical crack growth in water environment at 290°C

The results of fatigue crack growth rate measurements in air at room temperature are plotted against ΔK in Fig. 4 [4].

It could be reasoned that neither the threshold value for the fatigue crack propagation ΔK_{th}, nor the dependence of da/dN vers. ΔK are affected by strain ageing in spite of the significant differences in mechanical properties of studied steel in as received condition and after strain ageing.

Fractographic analyses of the fracture surfaces of failed specimens provide evidence that micromechanism of failure is not affected by strain ageing as well. Changing ΔK produced no significant change in micromorphology. Fields of strations and occurrence of transverse microcracks are considered to be typical microfractographic features.

Results of fatigue crack growth rate measurements in air and oxygenated water environment at 290°C as a function are ΔK of given Fig. 5 which shows a significant enhancement of fatigue crack growth rates compared with those in an air environment. Increasing the frequency of cyclic loading significantly lowered the kinetics of crack growth in water.

Experimental data fit very well with modified anodic dissolution/film rupture model [5]. Provided that the dissolved oxygen content was lowered significantly (see Fig. 6), no effect of the water environment was observed.

Fig. 7 shows δ - R curves obtained in water environment at 250°C and 290°C in aerated (O_2 > 5ppm) and de-aerated water (O_2 < 10 ppb) using increasing displacement tests of precracked C(T) specimens, at displacement rate of 0,001 mm/min. As the experimental data obtained in de-aerated water fit well with δ - R curves gained in air, SCC is not induced in the environment. However in the case of testing in aerated water environment, remarkably lower δ-R curves, compared with those of air, were obtained, confirming the susceptibility of the studied steel to SCC in the presence of oxidant at water temperatures higher than or equal to 250°C. From the quantitative point of view, the following differences were revealed by fractographic analysis of fracture surfaces produced by stable crack growth in aerated and deaerated water:

1. Vertical roughness of fracture surfaces produced in deaerated water is lower compared with that produced in aerated water.
2. Fracture morphology was characterized by the occurrence of areas with crack arrest markings separated by steps or secondary cracks. Distances between crack arrest markings produced on fracture surfaces in de-aerated water are shorter.

The effect of tube expansion technology on the residual stresses on the surfaces of holes

X-ray diffraction analysis was used for measuring residual stresses on the surfaces of holes for heat exchange tubes. The test pieces were cutted from central parts of experimental blocks (see Fig. 2c). The results of axial and tangential residual stresses measurements are summarized in tab. III and tab. IV. The obtained results show that an appropriate drilling technology results in compressive stresses on the hole surface lowering the probability of crack initiation. While explosive expansion technology produces tensile residual stresses, protective compressive stresses are lowered significantly by low temperature heat treatment (450°C/24h). On the other hand this heat treatment have little effect on the level of tangential tensile stresses produced by explosive expansion technology. But the level of tangential stresses is the driving force for environmentally assisted cracking of ligaments.

Tab. III: The effect of drilling and expansion technology on the level of tangential residual stresses

	as received condition	after 290°C/24h	after 450°C/24h
after drilling	-204 MPa	-100 MPa	-37 MPa
after hydraulic expansion	-308 MPa	-262 MPa	-60 MPa
after explosive expansion	131 MPa	89 MPa	205 MPa

Tab. IV: The effect of drilling and expansion technology on the level of axial residual stresses

	as received condition	after 290°C/24h	after 450°C/24h
after drilling	-204 MPa	-264 MPa	27 MPa
after hydraulic expansion	-658 MPa	-249 MPa	-54 MPa
after explosive expansion	164 MPa	152 MPa	-21 MPa

Conclusions

From the results obtained in this study it follows that:

1) Strain ageing of 10NiMo8.5 steel affected neither the threshold value K_{th} nor the dependence of the fatigue crack growth rate on ΔK.
2) A reasonable agreement between anodic dissolution/film rupture model proposed by Ford and Andresen and experimental data obtained at 295°C was noted.
3) Oxygen dissolved in water affects significantly the kinetics of fatigue crack growth behaviour.
4) Tube expansion technology doesn't affect fracture behaviour of ligaments both at 290°C and 320°C.
5) Operating temperature of cold collectors correspond to the upper shelf region of fracture behaviour of 10NiMo8.5 steel.
6) High temperature oxygenated water lower significantly δ-R curve compared with that in air.
7) Provided that the dissolved oxygen content was kept below 10 ppb no effect of water environment on fracture behaviour was found.
8) Appropriate drilling technology results in compressive stresses on the hole surface lowering the probability of crack initiation.
9) While explosive expansion technology produces tensile residual stresses, protective compressive stresses are produced by hydraulic expansion technology.

References

[1] FORD, F. P.: 3 Mechanisms of Environmentally Assisted Cracking. Int. J. Pres. Ves. and Piping 40 (1989), p.343.

[2] IAEA extrabudgetary programme on the safety of WWER NPPs. Final report of the consultans´meetings on steam generator collector integrity of WWER-1000 reactors. Vienna, May 1993, WWER-RD-0057.

[3] OHTANI, H.-McMAHON, C. J.: Modes of Fracture in Temper Embrittled Steels. Acta Meallurgica, Vol. 23, 1975, p.377.

[4] MATOCHA, K.-WOZNIAK, J.- SIEGL, J.: The Effect of Strain Ageing on the Propagation of Fatigue Crack in NiMoV Alloy Steel. In: Proc. of the IAEA Specialists Meeting on Thermal and Mechanical Degradation in Reactor Materials. Abington 19-21 November, (1991), p. 167.

[5] JAHNS, J.: The Corrosion Mechanical Damage of Low Alloy Steel of Type 10GN2MFA (10NiMo8.5) in Secondary Side Water Environment at 290°C, (in Czech.). Research and Development Division Report, CZ-10/96, Vitkovice, J.S.C., March, (1996).

[6] HIRT, J. P.: Metallurgical Transactions A, Vol. 11A, (1980), p.86.

[7] MATOCHA, K.- WOZNIAK, J.- JAHNS, J.- SIEGL. J - NEDBAL, I.: Subcritical Crack Growth Behaviour of 10NiMo8.5 Steel Type a 508 Cl. 3a Steel in Air and High Temperature Water. In: Proc. of seventh Int. Symp. on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors. Breckenridge, Colorado, Vol. 2, p. 1169.

[8] ESIS Procedure for determining the fracture behaviour of materials. ESIS P2-92, January 1992.

[9] KIM, I. S.: Dynamic Strain Ageing Effect on Fracture Toughness of Vessel Steels. Presented at IAEA Technical Committee Meeting on Materials for advanced Water-cooled Reactors, Plzen, 14-17 May 1991, Czech Rep.

[10] MATOCHA, K. - WOZNIAK, J.: The Effect of Strain Ageing on Fracture Behaviour in Air and High Temperature Water at Operating Temperatures of Collectors, (in Czech), Report of Research and Development Div., VÍTKOVICE, J.S.C., CZ-50/95, June, 1995.

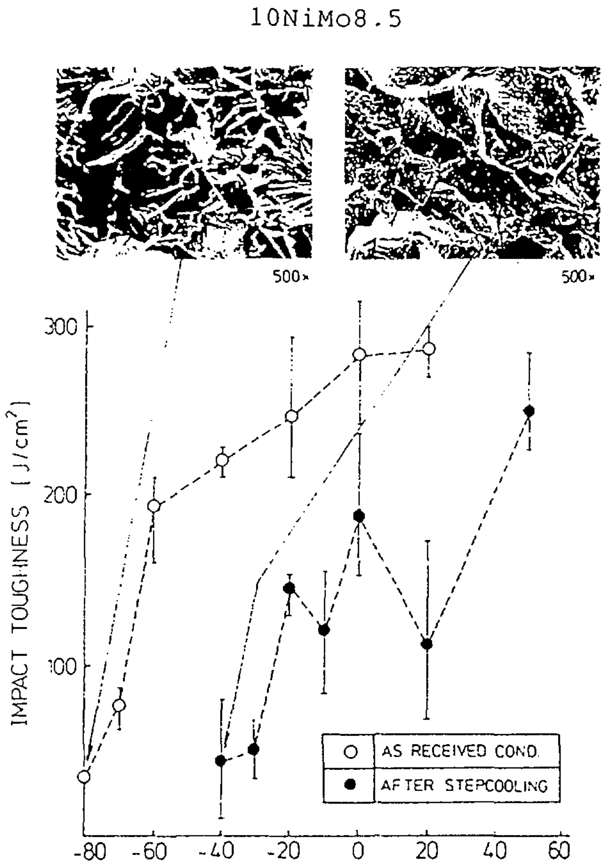

Fig. 1

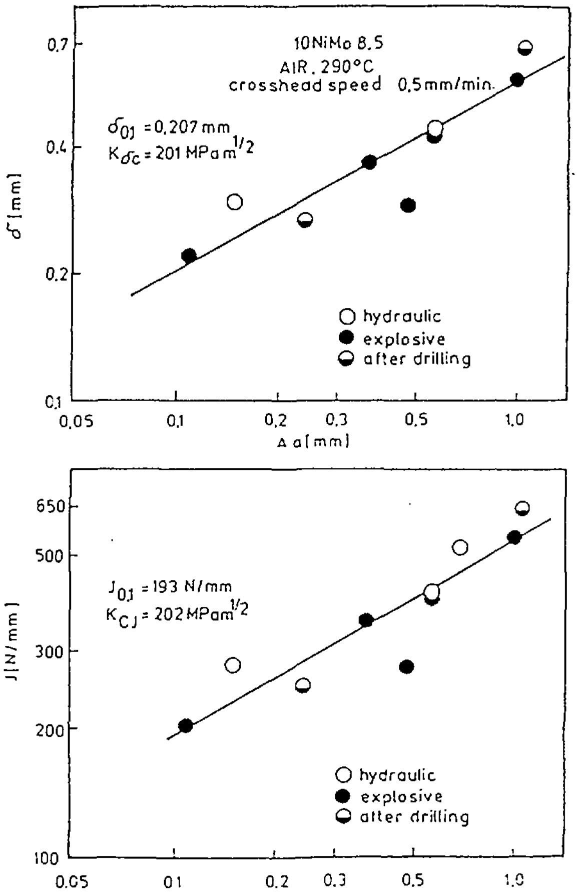

Fig. 3

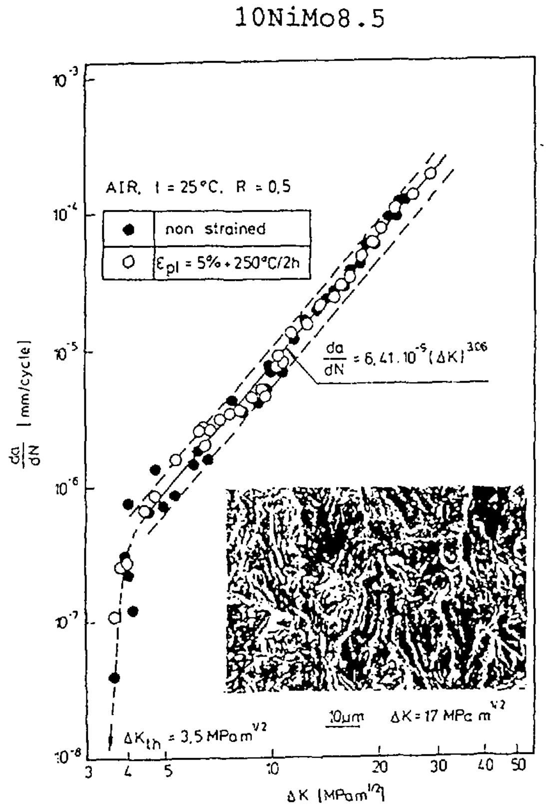
10NiMo8.5
AIR, t = 25°C, R = 0,5
● non strained
○ ε_{pl} = 5% + 250°C/2h
$\frac{da}{dN}$ = 6,41 . 10^{-9} (ΔK)$^{3.06}$
10µm ΔK = 17 MPa m$^{1/2}$
ΔK$_{th}$ = 3,5 MPa m$^{1/2}$
$\frac{da}{dN}$ [mm/cycle]
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
3
4
5
10
20
30
40
50
ΔK [MPam$^{1/2}$]

Fig. 4

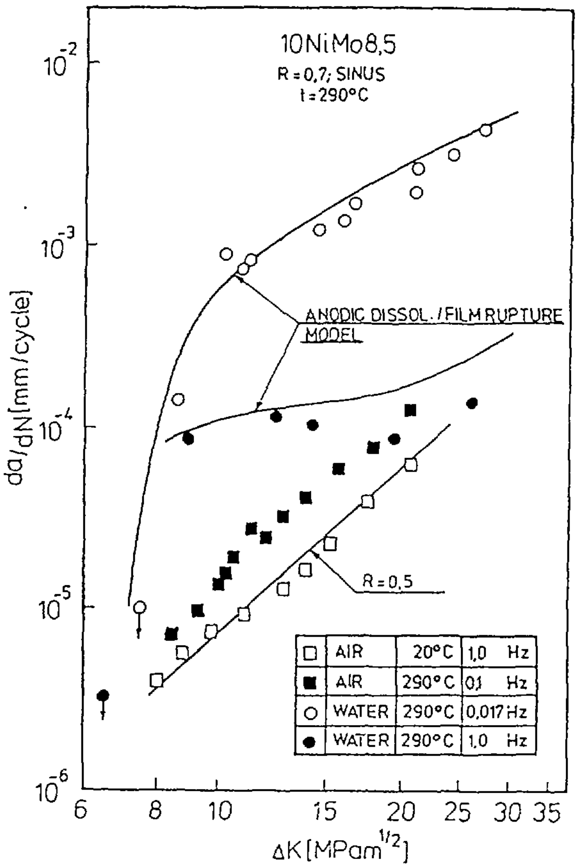
10NiMo8,5
R = 0,7; SINUS
t = 290°C
ANODIC DISSOL. / FILM RUPTURE MODEL
R = 0,5
□ AIR 20°C 1,0 Hz
■ AIR 290°C 0,1 Hz
○ WATER 290°C 0,017 Hz
● WATER 290°C 1,0 Hz
da/dN [mm/cycle]
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
6
8
10
15
20
25
30
35
ΔK [MPam$^{1/2}$]

Fig. 5

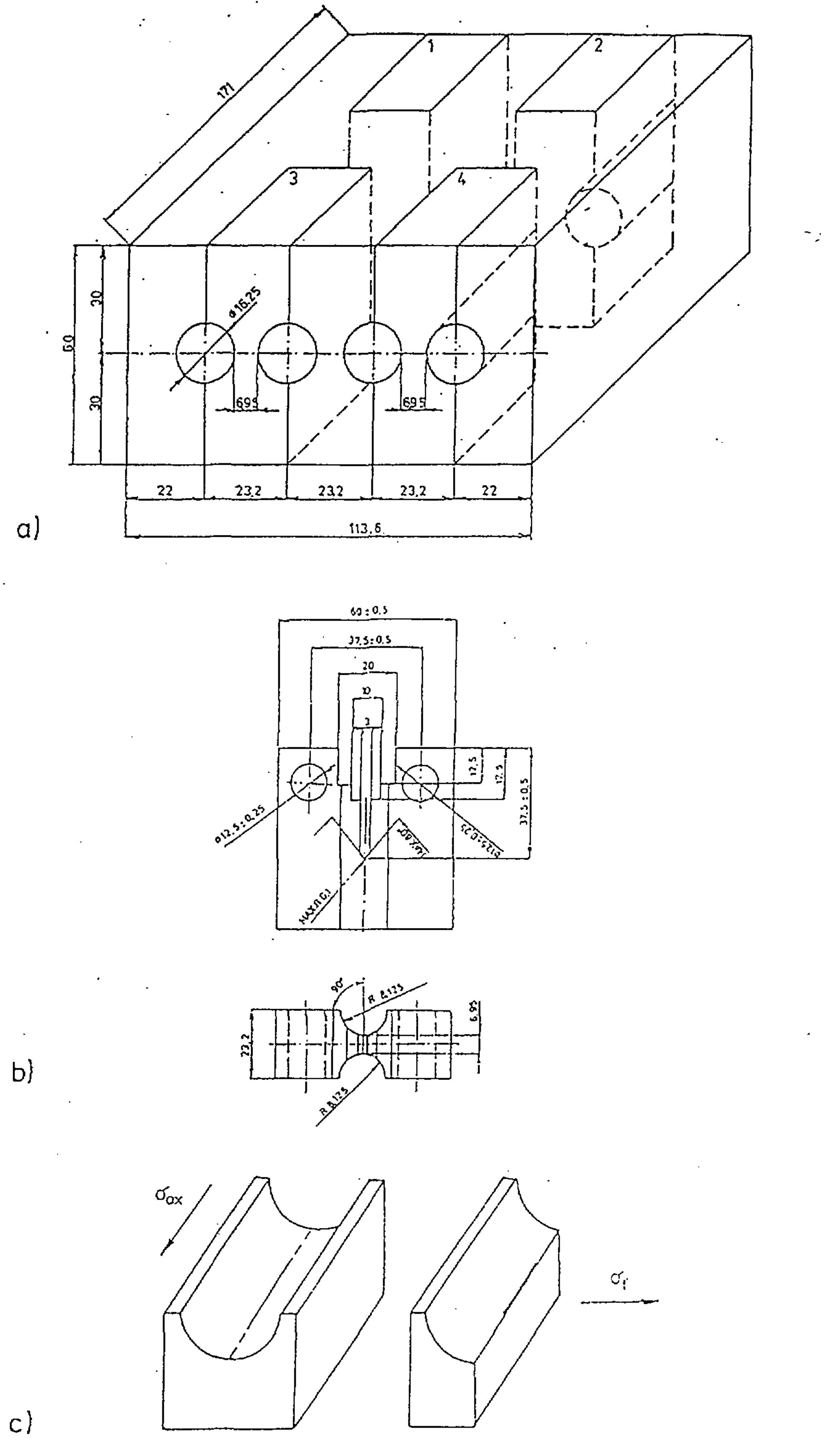
171
1
2
3
4
60
30
30
ø16,25
6,95
6,95
22
23,2
23,2
23,2
22
113,6
a)
60±0,5
37,5±0,5
20
10
3
12,5
17,2
37,5±0,5
ø12,5±0,25
ø12,5±0,25
MAX R 0,1
b)
90°
R 8,125
R 8,125
23,2
6,95
c)
σax
σr

Fig. 2

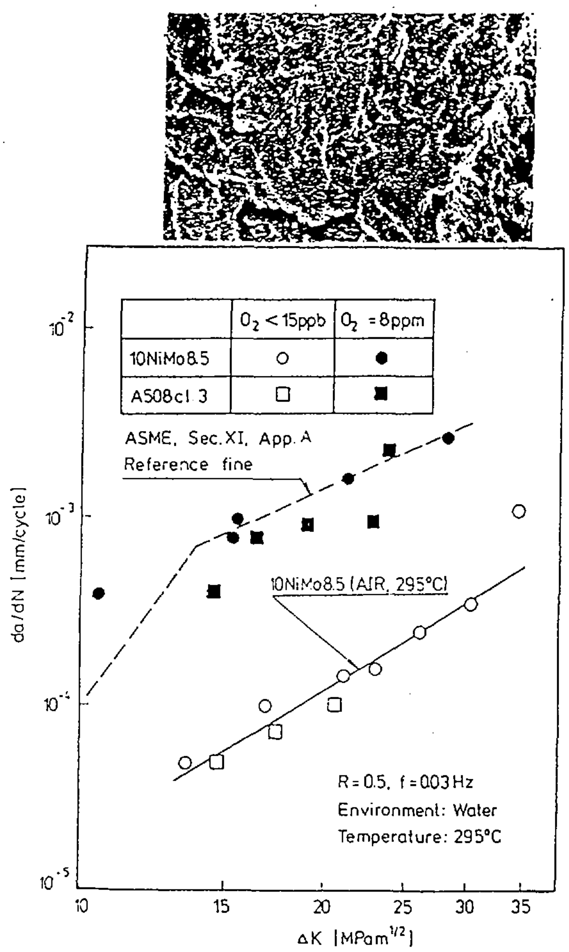
$O_2 < 15ppb$
$O_2 = 8ppm$
10NiMo8.5 ○ ●
A508cl 3 □ ■
ASME, Sec.XI, App. A Reference line
10NiMo8.5 (AIR, 295°C)
R = 0.5, f = 0.03 Hz
Environment: Water
Temperature: 295°C
10^{-2}
10^{-3}
10^{-4}
10^{-5}
da/dN [mm/cycle]
10
15
20
25
30
35
ΔK [MPam$^{1/2}$]

Fig. 6

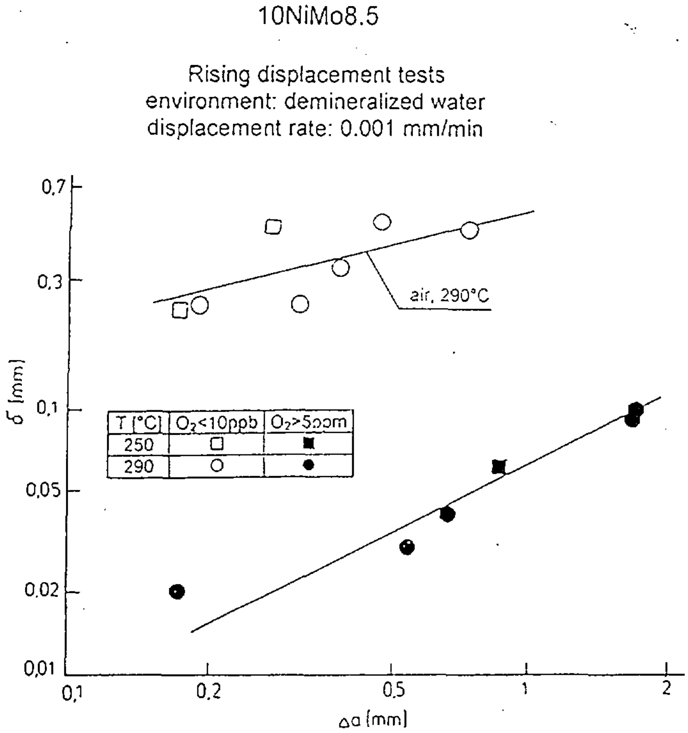
10NiMo8.5
Rising displacement tests
environment: demineralized water
displacement rate: 0.001 mm/min
T [°C] | $O_2 < 10ppb$ | $O_2 > 5ppm$
250 □ ■
290 ○ ●
air, 290°C
δ [mm]
0,7
0,3
0,1
0,05
0,02
0,01
0,1
0,2
0,5
1
2
Δa [mm]

Fig. 7