FAILURE ANALYSIS OF A 304 SS GIRDLING LOOP OF THE BOILER IN A 500 MW THERMAL POWER PLANT

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Introduction

There were many cases of girdling loop failures in the reheater section of the 500 MW boilers of a thermal power station after being in service relatively for a short period of a few months. Within seven months of synchronization, the bottom 'U' portion of the front reheater girdling loop of the boiler of 500 MW thermal power plant had developed a leak. The plant was restarted after replacing the failed protion of the type 304 stainless steel 'U' tube. Failure occurred again within seven months of operation. Similar failures followed in the other units of the station. The composition of the tube material was 0.059% C, 18.5% Cr, 8.7% Ni, 1.8% Mn, 0.49% Si, 0.01% S and 0.029% P. Four tube samples S1, S2, S3 and S4 (see fig. 1) cut from the failed girdling loop were sent to us for investigation of the failure. A new reference bend (Fig. 2) of the same materials was also received. The following investigations were carried out.

Visual and Steromicroscopic Examinations

Visual examination of the failed portion of the girdling loop showed a star likeopeining at the bend of the U tube (fig. 1). This opening was of smaller size at the inner wall of the tube compared to that on the outer wall. Both visual and stereomicroscopic examinations revealed flow patterns on the tube wall at the opening, suggesting that this large opening was formed as a result of leakage of high pressure steam from inside of the tube. A steam wash dimple was seen on the inner surface of the tube on the side opposite to the opening. Figures 3a and 3b are stereomicroscopic pictures showing characteristic features of erosion at the edges of the opening. The inner surface of the tube had two long cracks extending from the hole. stereomicroscopic examination also showed cracks starting from inner surface of the tube and running across the wall thickness. The oxide scale on the inner surface of the tube had cracked at many places. Bright, colourless salt crystals were also seen embedded in the oxide scale at the inner surae of the tube.

Scanning Electron Microscopic (SEM) Examination

A small sample cut from the cracked portion of the tube was opened out and examined in a SEM. The fracture was of typical intergranular morphology (fig. 4a) and many areas of the fracture surface were covered by corrosion products (fig. 4b) suggesting a corrosion cracking mechanism for the failure. The SEM examination of the inner surface of the tube showed severe cracking of the oxide scale (fig. 5a) near the cracked portion of the tube. Intergranular corrosion attack was also noticed (fig. 5b) in some regions where the oxide scale was damaged. Bright salt crystals embedded in the oxide scale were also seen in this region.

X-Ray Photoelectron Spectrocopy (XPS)

The oxide scale on the inner surface of the tube was analysed using XPS in order to understand the nature of the salt deposits on the tube surface. Apart from Cr, Ni, Fe and C (whose spectra are not given here), elements such as Na, Cl and Ca were detected indicating the presence of Na and Ca salts possibly in the form of their chlorides on the inner surface of the tube. Figures 6 and 7 give the XPS spectra showing peaks of Na and Cl respectively.

Evaluation of the Microstructure of the Tube Material

Since intergranular cracking of austenitic stainless steels is generally associated with the extent of sensitization in the steel, evaluation was carried out using the ASTM standard A 262 severely sensitized whereas the new tube was only slightly sensitized at the inner surface of the tube.

Metallographic examination of the failed tube was carried out after electrochemical etching in 10M KOH. No sigma phase was detected by optical microscopic examination of the etched sample. This is in line with the available information that precipitation of sigma phase is not expected in type 304 SS during the relatively short period of exposure in the temperature range of 520-570°C as experienced by the failed tube.

Residual Stress Measurements

Visual examination of the tube segments cut from the failed loop at the U-bend region showed ovality and thickness variations which are expected during cold bending. Residual stress measurements were carried out using XRD method. The equipment used was a portable X-ray stress analyser (Rigaku Strainflex MSF). Each point of measurement

Table - I
X-Ray Diffraction Conditions

Method	Parallel Beam Method
Characteristic X-ray	Cr K beta
Diffraction plane	(211)
Diffraction angle	156.5
Filter	V
Tube voltage	30 kV
Tube Current	10mA
Irradiated area	2 x 4 mm
x-ray fixed time	6 Sec.

was electropolished before measurement to avoid any surface altefacts. The conditions of X-ray diffraction are given in table I. The angles psi used were 0. 10, 20 and 30 degrees.

All the peaks were corrected for background and for absorption before peak location. Peak location was done by fitting a parabola at the top 20% of the corrected peak and top of the parabola was taken as peak top.

The measurements were carried out on the outer surface of the tube segment S4 (Fig.1) of the failed tube and also on the outer surface of the new tube. Residual stress on the inner surface was measured only in the failed tube section near the steam wash dimple (point 5 in fig. 1). The measured values of residual stress are presented in figs. 1 & 2. At one location one the failed tube segment S4. residual tensile stresses of 164 MPa (Circumferential) and 7 MPa (axial) were measured. Similarly a residual tensil stress of 133 MPa (circumferential) and a compressive stress of 180 MPa (axial) were measured at another point. At all other locations on the outer surface only compressive stresses were present both in the failed tube segment and in the new tube. Measurements were not carried out on the inner surface as this requires the sectioning of the tubes which will change the extent and pattern of residual stresses in the tube. The only measurement of residual stress done on the inner surface of the failed tube section has given a compressive stress value of 170 (axial) near the steam wash dimple. *Discussion*

The failure of the U-bend stainless steel tube of the girdling loop is not due to the embrittlement of the material produced by microstructural changes during the operation of the plant, as is evident from the fact that the cracking which was initiated from the inner surface of the tube did not propagate for longer distances or led to any catastrophic failure. Instead, as a result of erosion of the tube wall by leaking steam the crack was transformed into a large hole showing that the material had sufficient toughness to withstand high stress without fracture. Also, no embrittling sigma phase was detected in the failed material.

Measurements of sensitization in the failed as well as in the new tube have shown that the tube material has got severely sensitized during the operation of the plant because of exposure to temperatures in the range of 520 to 570°C. Although no intergranular stress corrosion cracking (ICSCC) of sensitized stainless steel is expected in the high temperature steam during the operation of the boiler. IGSCC is possible during the low temperature phase when residual steam in the tubes gets condensed on the tube walls. This condensate will dissolve all the salts deposited on the tube walls from thephase and will get collected in the bottom parts of the tube where the residual stresses also will be high near the bends, thus creating favourable conditions for IGSCC[1,2]. As the number of shutdown/start-up cycles increases the amount of salt deposited in the lower part of the tube also increases. Stereomicroscopic and SEM examinations of the inner surface of the failed tube have shown the presence of salt deposits and these have been shown to be chlorides of Ca and Na by XPS analysis. Thus the basic reason for the failure of 304 SS tube bends of the girdling loops appears to be IGSCC of sensitized steel in the presence of concentrated aqueous chloride solution during the period(s) of shut-down and start-up of the plant.

The only question that remains is that why no failure has occurred in other plants operating under similar conditions. It is reasonable to expect that variations in water chemistry and other operating parameters of different plants are mainly responsible for this.

Conclusion

The available evidence shows that the failure of 304 H girdling tube is due to intergranular stress corrosion cracking of the sensitized steel in the presence of chloride salts deposited on the tube surface, during the low temperature phase of operation of the reheaters.

Remedial measures

Intergranular stress corrosion cracking of stainless steels takes place if the following conditions are met:

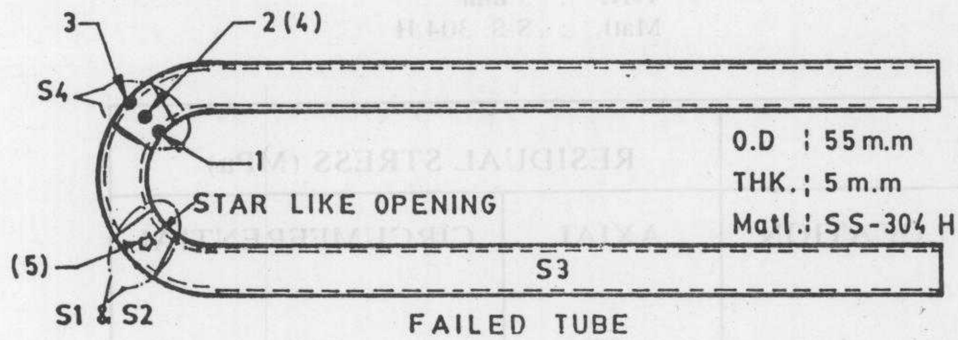
1. Sensitized microstructure
2. Presence of impurities such as chlorides in the solution phase
3. Tensile stress (applied or residual)

It is not possible to avoid sensitization in the present case since the operating temperature of 520-570°C is well within the sensitization temperature regime. However, sensitized steel is not prone to IGSCC in the steam phase of operation; but only in the condensate phase. Therefore, efforts need to be made to reduce the cold shutdown period to a minimum. It will also be advisable to keep the reheater tubes dry during the shutdown so that no condensation of water takes place on the tube walls. Strict control of feed water chemistry by keeping impurities such as chloride to the minimum possible levels will reduce the accumulation of chloride salts on the inner surfaces of the tube, thus reducing the potential for IGSCC. Since no applied stress seems to be present during the cold shut-down phase, residual stresses are likely to be responsible for the cracking process. The residual stresses may be reduced by furnace cooling (vis-a-vis the presently adopted air cooling) following solution annealing; however, furnace cooling is likely to sensitize the material excessively which can lead to IGSCC during precommissioning. Thus there seems to be not much scope for the reduction of residual stresses.

In the present case, detailed history of operation of the boilers has not been provided. Information such as total period of shut-down, number of start-up/shut-down cycles during the service of the failed tube and also a schedule of the start-up and shut-down operation are essential for a better understanding of the case of the failure. It will also be helpful if the chemistry of the feed water and the condensate during the service of the failed tube are provided.

References

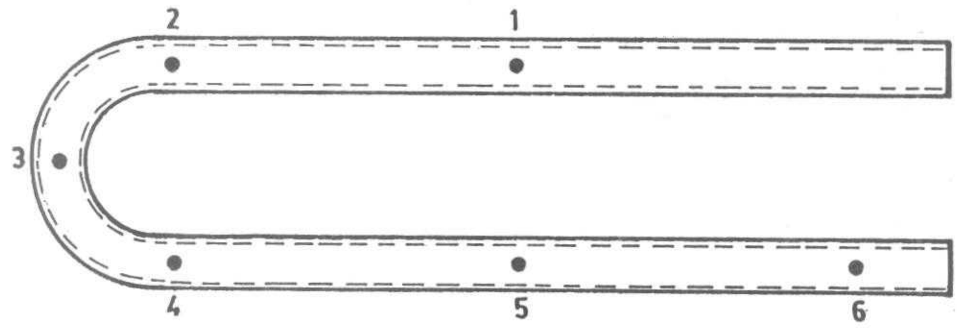
1. Modern power station practice. Chemistry and metallurgy, Volume E. British Electricity International. Pergamon Press. p.191 (1990).
2. Metals Handbook, Ninth Edition, Volume 13, Corrosion. ASM International, p.992 (1987).



	RESIDUAL STRESS (MPa)	
LOCATION	AXIAL	CIRCUMFERENTIAL
1	- 180	+ 133
2	+ 7	+ 164
3	- 343	- 95
4	- 200	- 319
5	- 170	-

Notes :
1. Points 1 & 3 are at diametrically opposite locatiosn similarly 2 & 4 are diametrically opposite point.
2. Points 1 to 4 are on the outer surface of the tube.
3. Pint 5 is on the inner surface of the failed section of the tube, near the steam-wash dimple

Fig. 1 : A schematic of the failed U-bend showing the pipe sections S1, S2, S3 and S4 and the locations where residual stress measurements were carried out. The measured values of residual stress aare also tabulated.



NEW TUBE
O.D : 55 m.m.
THK : 5 mm
Matl. : S.S. 304 H

	RESIDUAL STRESS (MPa)	
LOCATION	AXIAL	CIRCUMFERENTIAL
1	- 120	+ 21
2	- 170	- 153
3	- 110	0
4	- 140	- 76
5	- 154	- 146
6	- 134	- 121

Fig. 2 : A schematic of the new solution annealed U-bend showing the locations where residual stress measurements were carried out. Measured values of the residual stress are also tabulated.

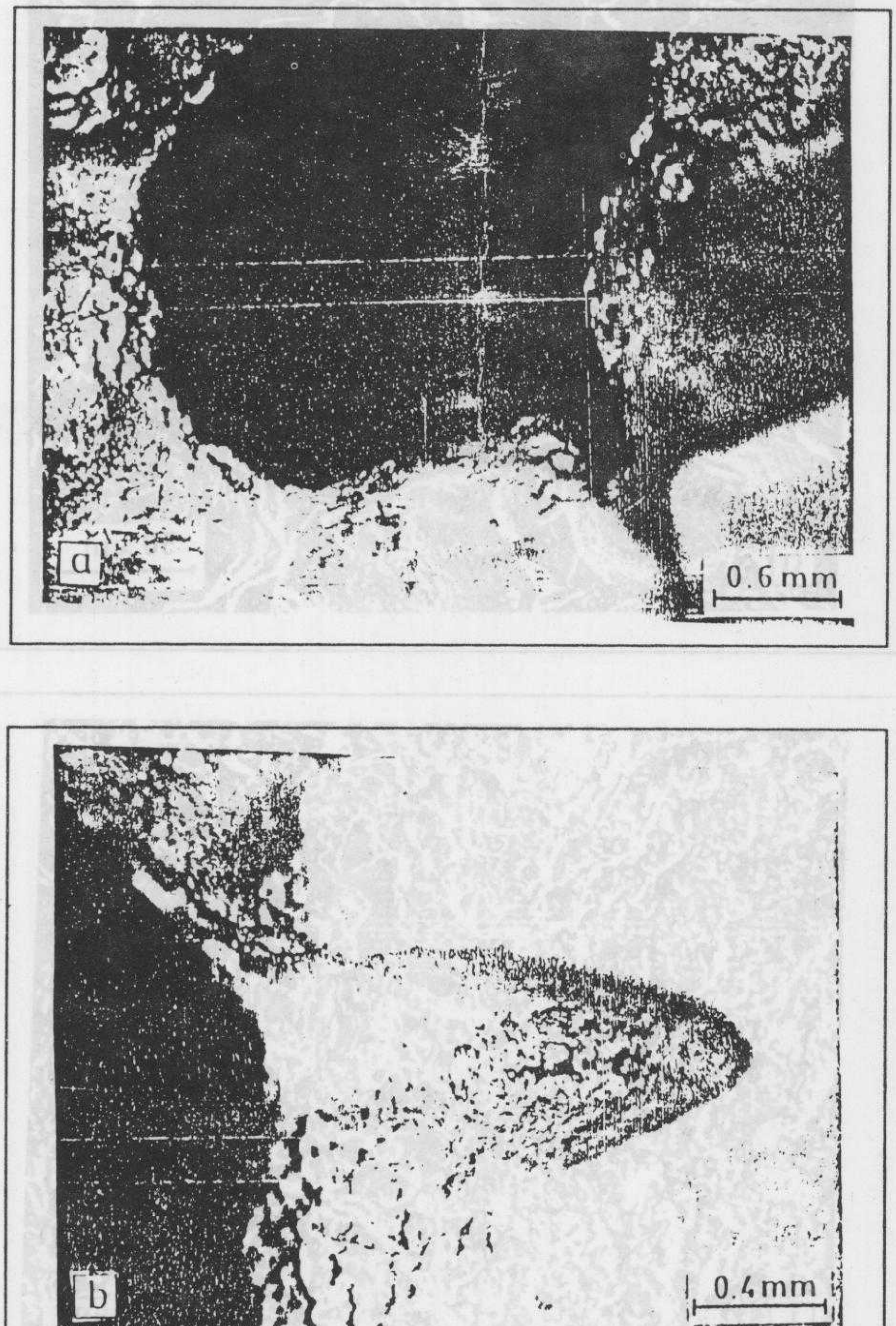


Fig. 3 : Stereomicroscopic pictures of the opening in the failed tube at different magnifications showing erosion of the tube wall

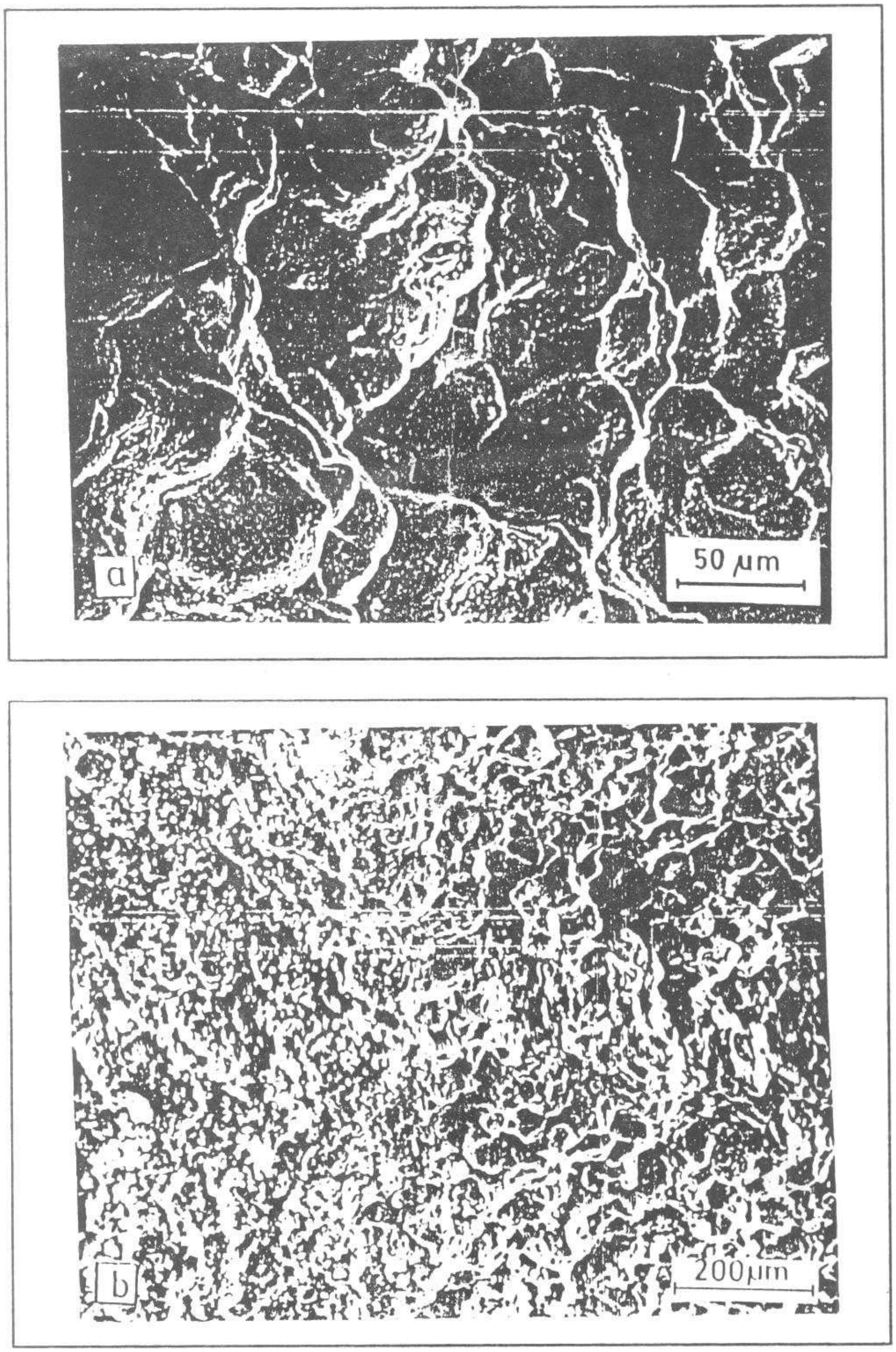
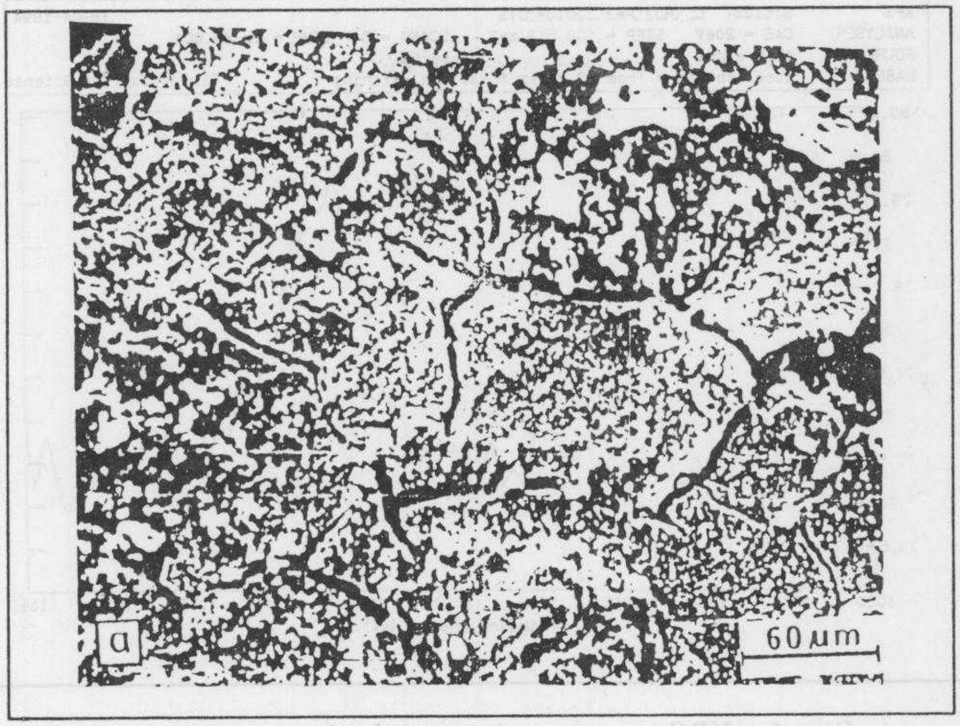


Fig 4 : SEM pictures of the fracture surface : (a) showing purely intergranular fracture, (b) showing a region covered by corrosion products and a region of intergranular cracking adjacent to it.



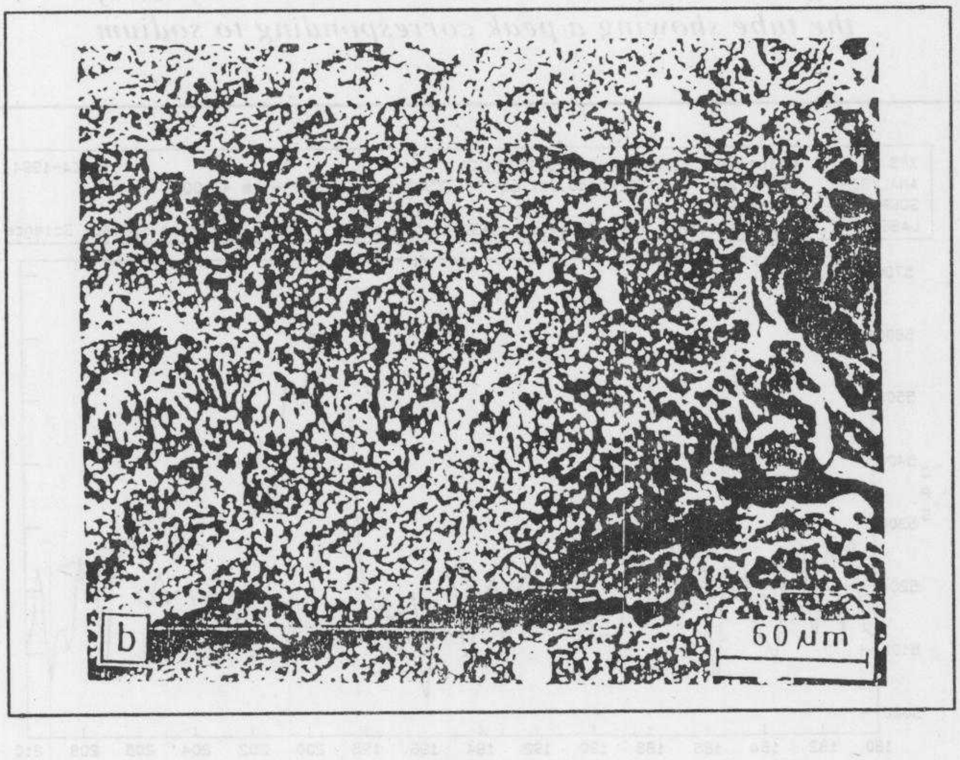


Fig. 5 : SEM pictures of the inner surface of the tube near the failed region : (a) showing cracking of the oxide scale, (b) a region of intergranular attack and a crack initiating from there; bright salt crystals are also seen in the picture.

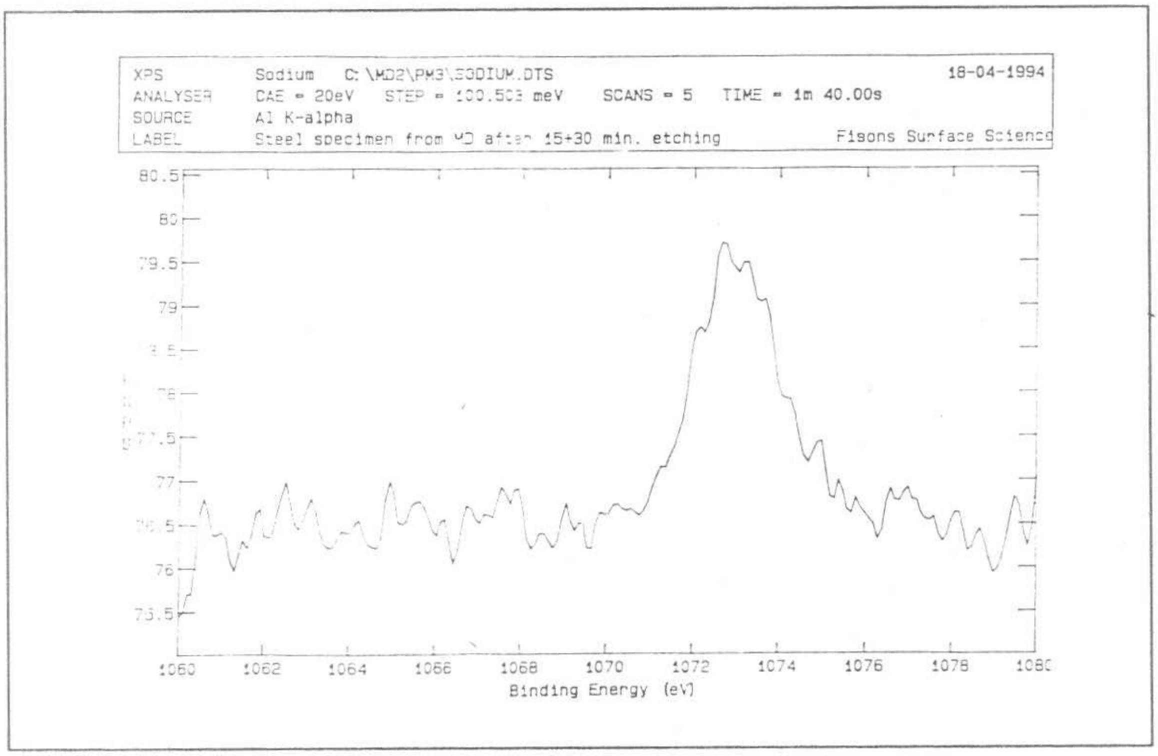


Fig. 6 : XPS spectra taken on the inner surface of the tube showing a peak corresponding to sodium

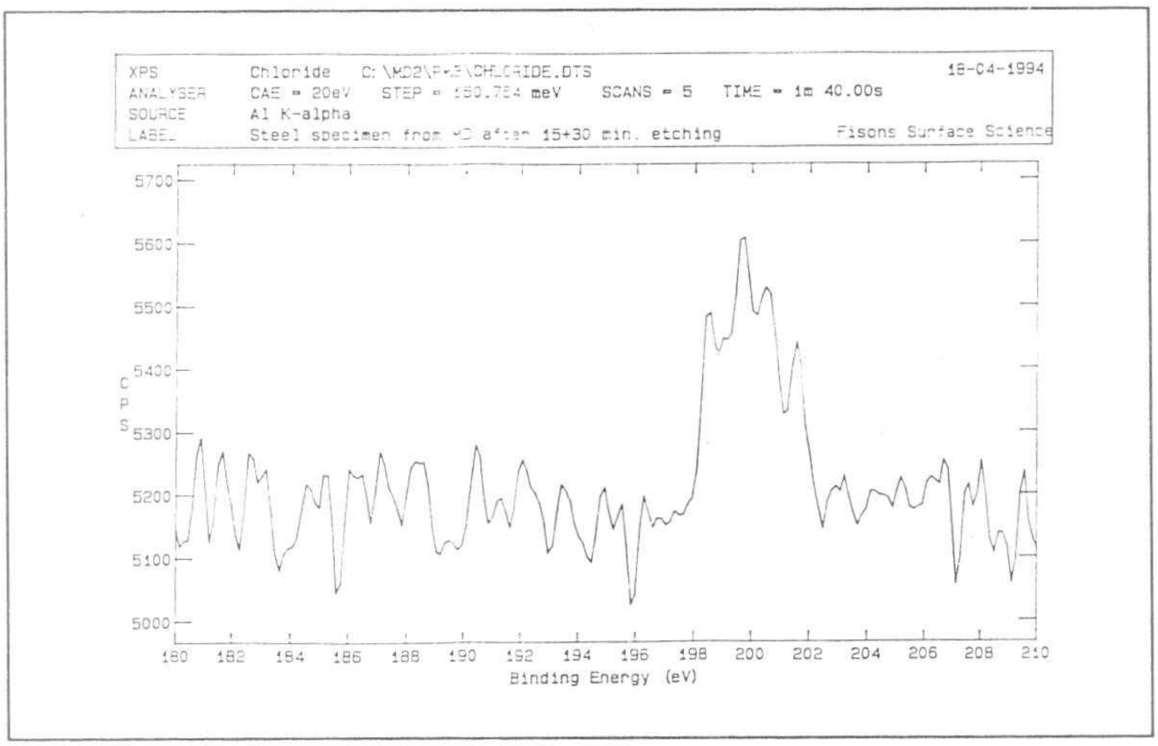


Fig. 7 : XPS spectra taken on the inner surface of the tube showing a peak corresponding to chloride