Failure Analysis of Welded Reformer Tubes of a Fertilizer Unit

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Abstract

A fertiliser unit experienced cracking of the circumferential weld of H39WM heater tubes at the hottest region along the vertical direction and particularly those closer to the wall. The cracks occurred in the internal side and observed to grow along the circumference. Longitudinal cracks were also seen in the inner wall. A few tube samples were examined to understand the cracking problem. The service exposed tubes show changes in carbide morphology and isolated creep voids are seen in the base metal and regions closer to the weld fusion line (heat affected zone). The longitudinal cracks are very close to the weld and creep void alignment away from the weld is very less. The circumferential crack show creep voids ahead of the crack and in regions close and parallel to the main crack. Isolated creep voids were observed mostly in the inner wall region and on the outer wall creep voids are absent. The creep cracking occurred in the weld of the hotter section as weld is the weakest link in the tube column.

Keywords: Creep damage, Weld failure, Reformer heater tubes, HP-microalloy,

1. INTRODUCTION:

Reformer furnace tubes are vertical tube columns containing the catalyst through which steam and natural gas is passed at high temperature. The process gas undergoes reforming reaction where by hydrogen rich gas essential for ammonia forming is produced. The inlet temperature of the process gas is around 450-500^0 C and at the outlet manifold it is 800-900^0 C. The pressure ranges from 1-4 MPa. Typically the reformer tube columns are made of tubes of 10-15 m in height and 100-200 mm in diameter and 10-25mm in wall thickness. The tubes are centrifugally cast high carbon, creep resistant austenitic steels such as IN519 (H24W – 24Cr-24Ni1Nb-0.4C), HP-Nb modified (25Cr-35Ni-1Nb-0.4C) and HP-W modified ((25Cr-35Ni-0.5W-0.4C). The temperature of the tube wall depends on many factors and it is not uniform along the vertical section and with the time of service the temperature distribution changes due to several factors like burner regulation, loss in catalyst activity, ageing of catalyst, collapse of catalyst column inside the tube [1-4]. Though the design life is nominally 10^5 h (11.4 year), available information on service life found to vary from 3 to 15 years [2]. Creep of the tube material, thermal shock, overheating and carburisation of the inner wall are some of the damage process which cause premature failure of the hot section parts of reformer tubes [1-5]. A fertilisers manufacturing unit experienced failures in the welded section of primary reformer tubes of ammonia plant. The investigation findings of that failure and remaining life estimate are presented here. .

2. TECHNICAL BACKGROUND

The failure occurred in the reformer section of Ammonia-Urea fertiliser complex having a capacity to produce 1100 MT of ammonia and 1650 MT of Urea per day. The primary reformer section of ammonia plant is top fired steam reforming furnace having catalyst tubes arranged in equally spaced 8 rows each with 42 tubes per each row and one riser tube at the centre of each row (total 336 catalyst tubes and 8 riser tubes). Each catalyst tube is manufactured by centrifugal casting process having three segments which are joined together by welding. The tube material is G4852 modified (generally referred as HP microalloyed) manufactured by M/s Schmidt & Clemens GmbH. The nominal chemical composition (in wt.%) of the tube material is as follows: - Cr:23-28; Ni:33-38;Si: 1.5 (max); Mo:0.5 (max); Ti:0.30 (max); Nb:1-1.5; Mn:1.5(max); C:0.35-0.45; P:0.03 (max); S:0.02(max) microalloying– proprietary. The catalyst tube nominal dimensions are 82 mm I.D and O.D.107.6mm. The maximum temperature is experienced in the "C" weld zone. The actual temperature recorded at this zone was 870^0 C against the design temperature of 930^0 C. The operating pressure is 34 kg/cm^2. The inlet feed temperature is 550^0 C and the outlet temperature is 780^0 C ± 5^0 C.

The reformer tubes were in service for 10 years. During annual shutdown radiography examination revealed that 55 nos. of reformer tubes and 3 riser tubes were having cracks initiating from inside in "C" weld. Out of these tubes, one riser and 25 nos. of catalyst tubes were repaired as cracks were of moderate depths. These tubes were replaced back in service after re-welding. Before re-welding the tube ends were "solution annealed" at 1100^0 C, followed by air quenching. The maximum numbers of failure of the tube was in row No.1 (7 Nos.) and in row No.8 (8 Nos.). Both these rows were near the wall of the furnace. From the dimensional measurements record it was found that in row No.1, creep was mainly less than 0.73%; only 2 Nos. of tubes showed creep in the range 0.73 to 1.3% and only one tube showed creep in the range of 1.3 to 2.5%. In row No.8, 6 Nos. of tubes showed creep in the range of 0.73-1.3% and 10 Nos. of tubes showed creep in the range of 1.3 to 2.5%. A few tubes in other rows – two in row No.3 and one in row No.4 also showed creep in the range of 1.3 to 2.5%. It was reported that in the 5th year of its service, accidentally the temperature of the furnace had shot up to 1000^0 C for a few hours.

The following pieces from the reformer tubes were received for the investigation:
(i) Ring pieces of "C" weld from tube Nos. 834 and 140 which were found to have cracks on the inner surface side of the weldment (Fig.1) (ii) One tapered section of base metal of tube No.840 (Fig.2) (iii) Samples from tube No.831 consisting of (a) one piece of 12 inch length from just above the end of C weld joint in the service exposed condition (here onwards referred as tube 831-C weld-SE) (b) one piece of 12 inch length from just above the end of C weld joint in the solution annealed condition (here onwards referred as tube 831-C weld-SA) (c) one piece of 12 inch length from "D" weld joint (with the weldment at the centre) in the service exposed condition (here onwards referred as tube 831-D weld-SE)

3. VISUAL EXAMINATION

In both ring pieces, crack originated on the inner surface side on the weld root, which appeared to have grown in the circumferential direction (Fig.1). The crack length is 24 mm, depth is 3.7 mm and the crack opening is 0.6mm in the tube No.834 where as in tube No.140 it is 17mm, 4mm and 0.35mm respectively. There were no visible cracks in the base metal adjoining the weldment or in the weld root at sites other than the one shown in Fig.1

The tapered section of the base metal showed crack originating from the inner wall side and extending towards the outer wall (Fig.2). The crack is of sufficient depth covering about 2/3 of wall thickness. On the outer wall side no cracks were visible. On polishing and etching this sample, it was revealed (micrograph details are given later in this report) that the tapered section is not fully of the base metal. About 2 mm of weld region is also present and the cracks were actually in this weld region and base metal close to it i.e. heat affected zone (HAZ). These cracks propagated longitudinally on the inner surface. More number small longitudinal cracks were also observed on the inner wall and close to the weld HAZ in addition to that shown in Fig.2

4. HARDNESS

The reformer tube samples were subjected to hardness testing using a Vickers hardness tester. The load applied is 30 Kg. Five readings were taken on each specimen and averaged. The results are presented in Table 1. The hardness values are with in the expected range typical for this grade of material.

5. TENSILE TESTING

Tensile test specimens were machined out from the base metal of tube no.831-Cweld-SE and tube no.831-SA samples. Tests were carried out at 900^0 C. Observed tensile properties are presented in Table 2 along with the standard data minimum value (taken from the manufacturer's data sheets available) at the same temperature

As seen from the table, some degradation in strength had occurred for tubes in the service exposure condition. Among the service exposed tube samples, Tube 831-Cweld-SE shows lower strength. Solution annealing has improved the tensile strength marginally. Comparing the tube samples of 831-Cweld-SE and 831-Dweld-SE, the latter shows slightly higher strength obviously due to lower operating temperature near the "D" weld region and as a result lower degree of ageing.

6. METALLOGRAPHIC EXAMINATION

6.1. Optical Metallography

Standard metallographic specimens were prepared from the tube samples. The microstructures of the specimen cut from ring piece of tube No. 140 are shown in Fig.3 Similar features were found in ring piece of tube No.834 and not presented here. The microstructures of tube 831-Cweld-SE and tube 831-Cweld-SA are represented in Fig.4 and for the tube 831-Dweld-SE in Fig.5. For all the figures the main features were mentioned in the caption.

In the unexposed condition, HP-microalloy will show primary eutectic like carbides both at the dendritic and equiaxed grain boundaries. Up on thermal exposure in service, primary carbides tend to grow and secondary precipitation occurs inside the grains. The observed microstructures for the sample under investigation show this behaviour clearly. In the service-exposed specimens, the primary carbides are linked up and blocky at some places and secondary carbides are also showed some degree of coarsening. Service exposed tubes showed isolated cavitation in the base metal mainly near the inner surface weldment. In the weldment coarsened primary carbides and fine secondary carbides were observed.

In tube No.140 (Fig.3) and No.834, the crack was observed on the inner surface propagating in the circumferencial direction along the weldment. Also, aligned creep voids and joining of these aligned voids to form microcracks in the circumferencial direction were observed ahead of the main crack. Cracks were also observed in longitudinal direction on the inner surface in the region of the base metal very close to the weldment i.e. HAZ. As one moved away from weld region, the creep voids are less aligned and mostly isolated.

The main circumferential crack in the weldment was observed to have longitudinal branches extending on to the base metal**.** On closer examination it was revealed that the longitudinal cracks were originated in the edge of weld heat affected zone and leading on to the base metal (Fig 3e). The weld did not show cracks or voids through out the circumference on the inner wall side. Similarly longitudinal cracks in the base metal adjacent to the weldment appeared only in regions where the weldment had cracked although the isolated creep voids in the base metal close to the weld are uniformly distributed on the entire circumference on the inner wall side.

Unlike the tube No.140 and No.834, the weld of tube 831-D weld-SE did not show (Fig.5f) any creep induced cracks although the base metal showed isolated creep voids in the regions close to inner wall and mid thickness. Absence of creep induced cracks and aligned voids in the weld may be due to the lower temperature experienced at the "D" weld zone.

In the tapered section sample, base metal with the visible crack appeared to extend towards the outer wall (Fig.2), optical metallography showed (Fig.6) that these cracks were longitudinal and existed in the HAZ and the base metal adjacent to it. A number of longitudinal cracks were observed on the base metal closer to the weldment on the inner wall surface. The cracks were growing due to coalescence of aligned creep voids. As one move (about 10mm) from the weld line, the longitudinal cracks were absent but isolated creep voids without preferential alignment were observed.

6.2 Scanning Electron Microscopy (SEM)

Standard metallographic specimens were prepared and slightly over etched for better relief of the precipitates for SEM examination. Typical microstructures observed for the tube samples under investigation are shown in Fig.7. As observed in the optical microscopy, coalesced primary carbides in the grain boundaries and secondary carbides inside the grain were observed. In some cases the secondary carbide is very fine. It may be recalled that the tubes had experienced temperature around 1000^0 C for few hours during operation in its 5^{th} year. At such high temperatures, the secondary carbides may dissolve and reappear when the temperature is lower in the region of $850\text{-}900^0$ C. Coarsening of carbides is observed in the equiaxed zone and in the inter-dendritic region of the base metal. The circumferential weld showed voids only ahead of the crack. The EDAX analysis on the grain boundary precipitates (appearing as greyish in Fig.7) both in the base metal and weldment showed that they are chromium carbides of the type $Cr_{23}C_6$. Inside the grains the secondary carbides are also of the same type. In addition, inside the grains very fine precipitates (appearing as white in Fig.7) rich in nickel, niobium and silicon were found. The compositions of the precipitates are given in Table 3:

7. DISCUSSION

Cast microstructure of the reformer tube material undergoes changes in carbide morphology up on exposure to high temperatures in service [4-11]. The exposure temperature is more significant in causing the microstructure changes than the exposure time [3]. The creep damage in reformer tubes are observed in the form of aligned voids and multiple cracks. Reformer tubes have shown two kind of tendency for void alignment. If the cast tube parent metal is the weak link then the voids are aligned in the longitudinal planes with in the tube. When the weak link is the weld the voids alignment is localised in a plane transverse to the tube axis and lying either in the centre of the weld or with in the heat affected zone [1-3]. Further, in a given tube different levels of creep life consumption can be attributed to different sections of the tube based on distribution of the voids and cracks. The useful life of weld in a reformer tube is often limited by the propagation of the cracks in the plane of the weld and lying with in the weld deposit. Cracks appearing in the heat-affected zone may also play as an important factor. Rarely, the crack transverse to the weld, lying along the tube axis and extending in to the base metal becomes the life-limiting factor.

In the present case of failure investigation, observed microstructures indicates clearly that damage had set in the form of creep with the inner wall showing creep voids. Though creep voids are in the base metal only tube weld cracked and showed more aligned voids and cracks in the circumferential direction. Thus in the HP microalloy materials the weld is the weakest link.

Some important points emerging from microstructural examinations are:

- Coarsening of the primary carbides and secondary carbides clearly indicates that ageing has well set in the tube material more particularly in the high temperature zone of "C" weld.
- Creep voids in the base metal appeared to have formed at the carbide/matrix interface
- Creep voids have formed in both the weld and in the base metal (Fig.3&7) of the failed tubes
- Creep voids /cracks in the weldment are located only in the region ahead of the main crack
- In the base metal, isolated creep voids are distributed uniformly. Alignment of these voids occurred only in the region very close to the fusion line i.e HAZ, leading to the longitudinal cracks in the base metal
- Crack in the weld region have propagated in the circumferential direction owing to poor creep ductility of the weld
- Creep voids were mainly present on the inner side of the tube (equiaxed grain boundaries) and at some places in the mid-wall. The columnar dendritic grains near the outer wall were found to have no creep voids.
- Creep caused cracking more in the weldment than in the base metal due to poor creep ductility of the former
- Energy dispersive X-ray (EDX) analysis of the precipitates did no show any significant difference between carbides present in the base metal and the weldment.
- Solution annealing brought about dissolution of secondary carbides (Fig.7d), which should improve the weldability.

The failure of the reformer tube has taken place due to propagation of crack in the circumferential direction in the weld region. This has happened due to excessive creep deformation experienced by the tube during service exposure as borne out by the presence of creep voids at all the places, particularly on the inner surface. Indeed creep measurement has also shown good amount of creep deformation in some tubes especially those near the walls. The reason for the formation of creep voids mainly on the inner surface appears to be due to the fact that equiaxed grains have poorer creep ductility than the columnar grains. It may be noted that the creep voids in the base metal are isolated whereas those in the weldment and in the HAZ have linked up and the weldment cracks propagated more so in the circumferential direction. Any "left out" cracks in the weld zone in some of the tubes can be expected to grow in course of time. This is more to be expected in rows 1-8 where furnace temperature could be higher being nearest to the wall. In the absence of long term creep test data and creep crack growth data for the base metal and weld as well for the HP-microalloy, remaining life prediction becomes difficult. More research efforts are needed in these aspects. Since only isolated creep voids are observed and post service annealing improves the carbide morphology one can expect some good amount of remaining creep life, How ever this need further experimental confirmations through test on service exposed material. Weld repair done at the site can be considered to be healthy provided pre-existing cracks in the base metal (adjacent to the weld - Fig.6) were removed while edge preparation.

In view of uncertainty in the remaining life of the weld joints, it is advisable to go for the replacement of the tubes within one-two years. One favourable factor in case of weld joint is that the crack is growing more circumferentially and very less towards the thickness of the tube. Ultrasonic examination at the earliest opportunity is also recommended.

8. CONCLUSIONS

The failure of the weld of the HP-microalloy tube is in the form of circumferential crack on the inner wall side is due to the creep damage which was caused by the high temperatures experienced at this zone of the tube column. The crack appeared in the weld as it is weakest link even as the isolated cavities present in the base metal region. Isolated creep cavities are mostly from inner wall to the mid-thickness region. Outer wall region did not show creep voids. Longitudinal cracks appeared only in the HAZ region. Post service annealing to re-weld the tubes changes the carbide morphology. But, presence of isolated cavities is of concern for long term life prediction.

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Table 1. Vickers Hardness values of test samples of reformer tubes

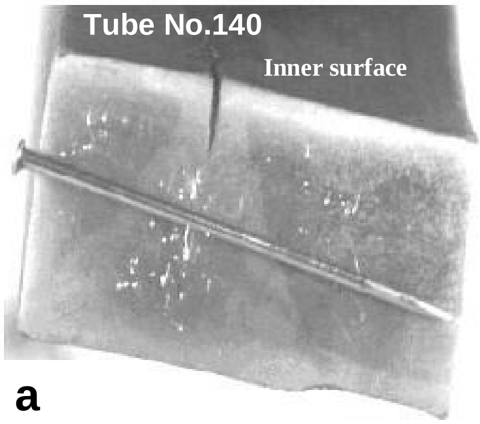
Specimen Identity		Hardenss Hv_{30}
Tube 140 ring piece	Weld	180
	Base	165
Tube 834 ring piece	Weld	176
	Base	167
Tube 831-C weld-SE	Base	168
Tube 831-Cweld-SA	Base	176
Tube 831 D weld-SE	Base	170
	Weld	176

Table 2. Tensile properties at 900^0 C for the base metal sample from tube no.831

Specimen Details	0.2% P.S., MPa	UTS, MPa	% RA	% El (GL= 25mm)
Tube 831-Cweld-SE	83	118	47	22
Tube 831-Cweld-SA	92	121	38	25
Tube 831-Dweld-SE	92	125	53	16
Unexposed sample standard data minimum	110	150	---	30

Table 3. EDAX results of the observed precipitates in the base and weld metalregion

Element	**Composition Wt%**	
	Greyish precipitate	**White precipitate**
Cr	81.61	24.92
Fe	12.26	9.93
Ni	4.50	43.50
Si	1.14	6.59
Nb	0.41	15.05
S	0.03	-----



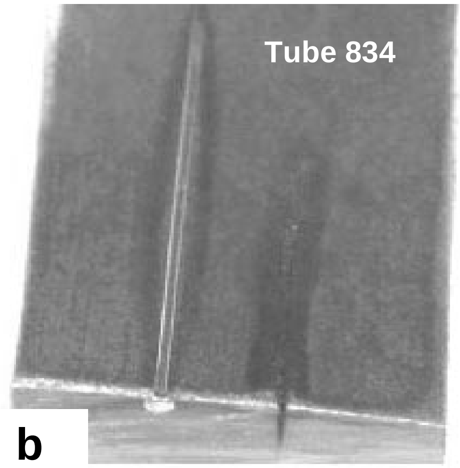


Fig.1.Macrographs of samples from tube received (a) showing crack originating from the inner surface (weld root) (b) showing crack growing in the circumferential direction

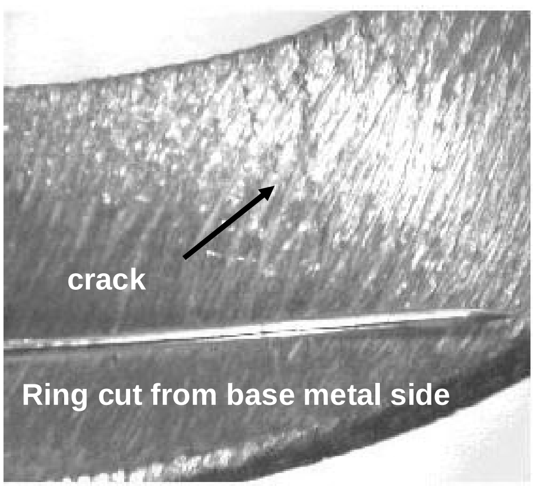


Fig.2 Macrograph showing the tapered ring section of tube No.840 with crack

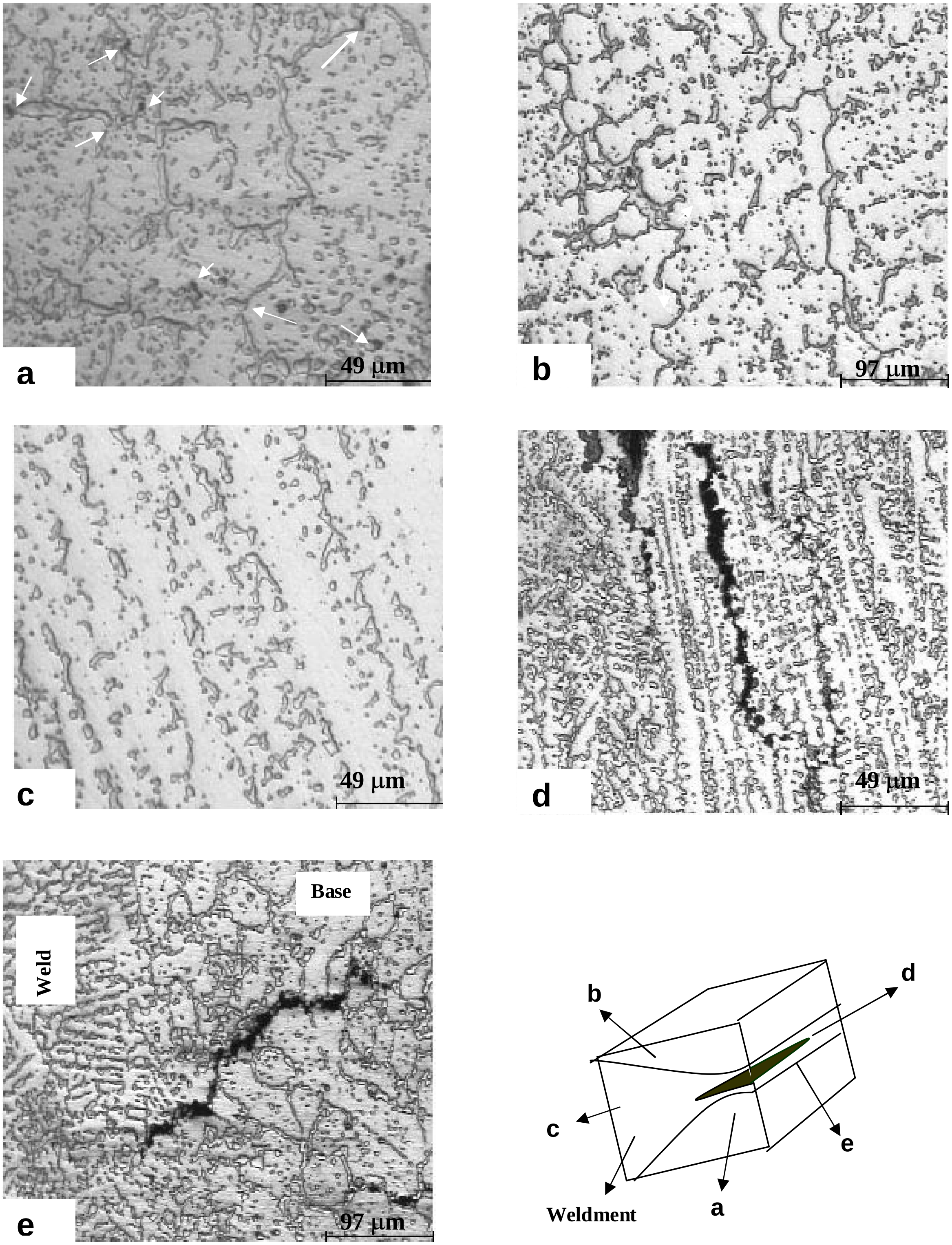


Fig.3. Optical micrographs of cracked weld of tube no.140 (schematic diagram show the location on the metallographic specimen) (a) equiaxed zone (b) columnar zone (c) weldment (d) ahead of crack on the inner wall in the circumferential weld (e) inner wall base metal near the fusion line. Arrows indicated creep voids

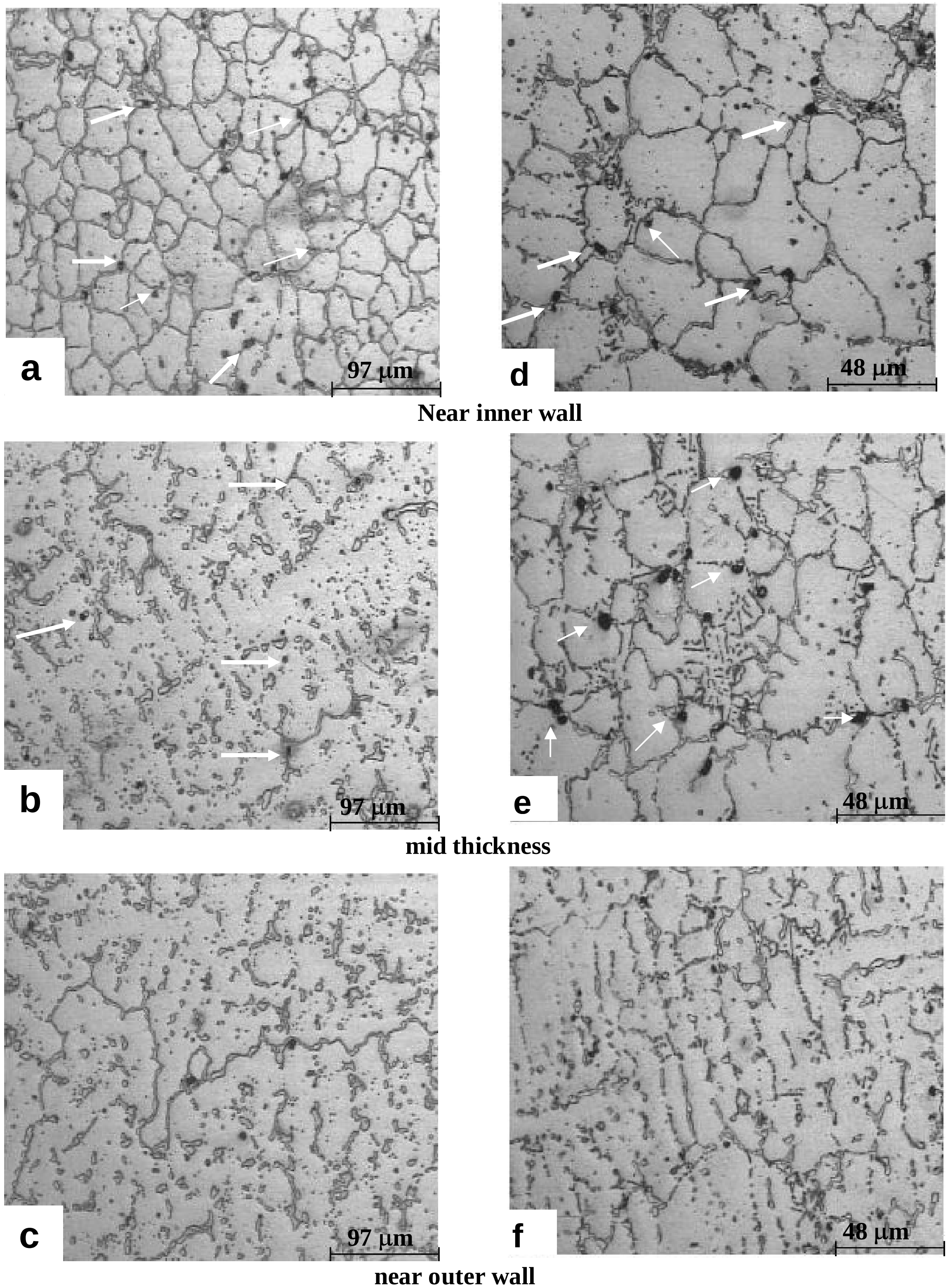


Fig.4. Photomicrographs of transverse section (a,b,c) tube 831-C-as service exposed. GB primary carbides are coagulated and continuous. Intragranular secondary precipitates are bulky. (d,e,f) tube 831-C-post service annealed. Change in carbide morphology. In both sample pieces isolated creep voids are present near the inner wall and mid thickness regions. Near the outer wall region creep voids are absent.

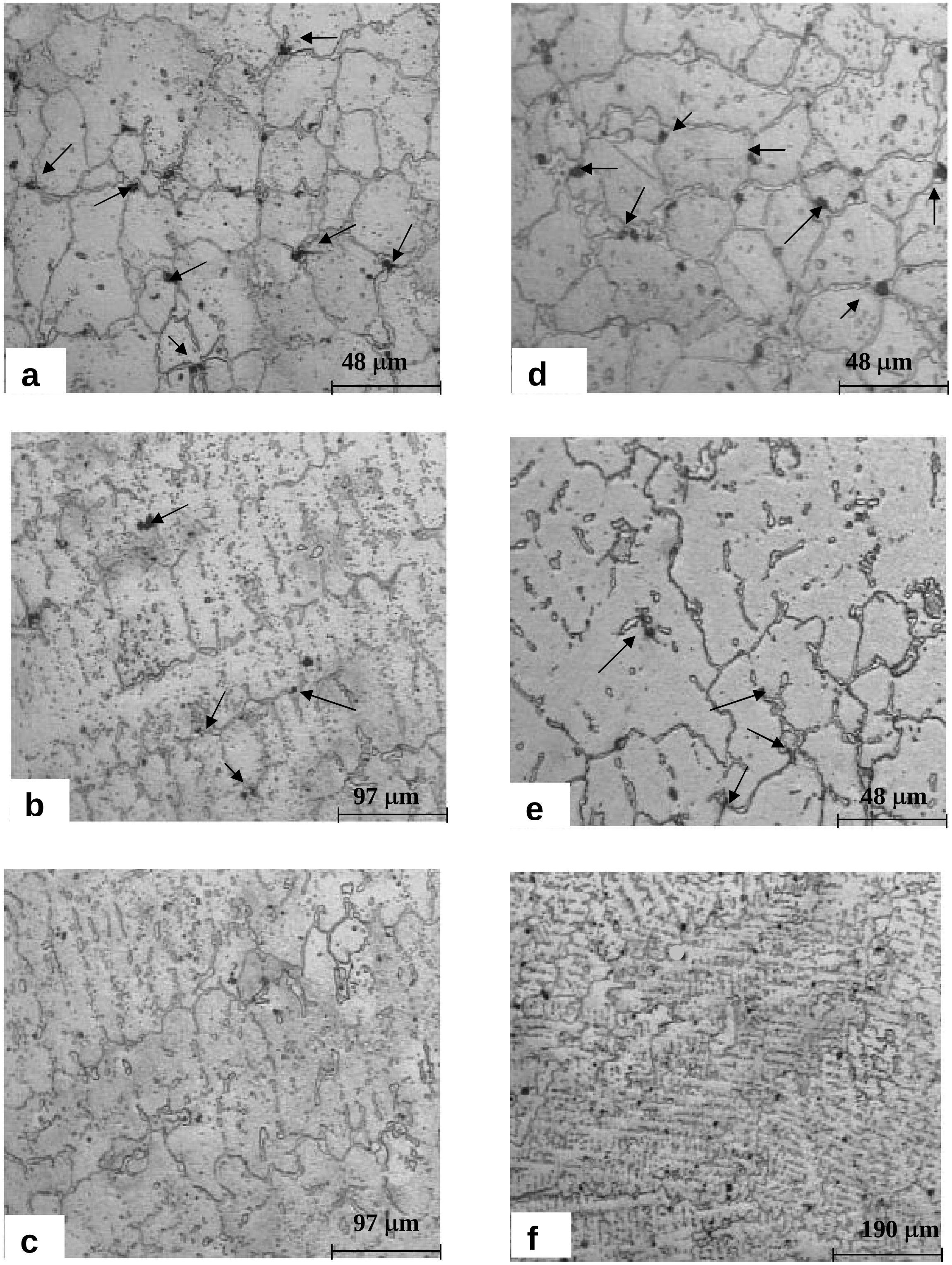


Fig.5 Photomicrographs of tube no831 cut from the 'D'weld region in the as exposed condition (a) near inner wall -.creep voids arrowed (b) near mid wall region-fewer creep voids (c) near outer wall-no creep voids (d) inner wall base metal adjacent to the weldment - creep voids present (e) mid wall region (f) weldment on the inner wall side showing no creep voids (the black dots are etching artefacts confirmed in SEM).**(a-c) LS= longitudinal section (d-f) TS = transverse section**

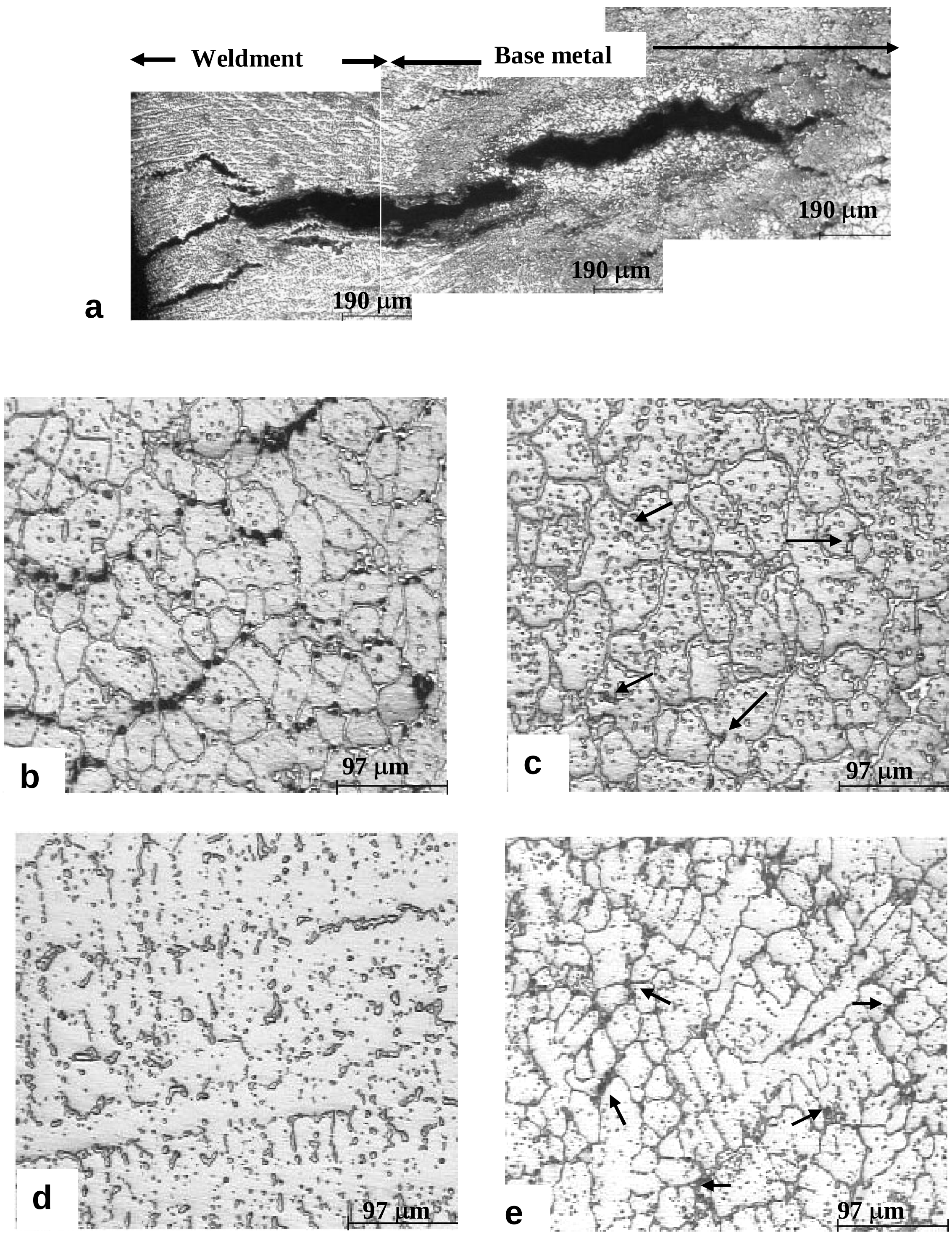


Fig.6 Photomicrographs of the tapered section base metal sample (a) the inner wall showing longitudinal cracks in the weldment and base metal close to it (b) inner wall – equiaxed grains close to the weldment – aligned creep voids induced cracks (c) inner wall – equiaxed grains well away from the weld – only isolated creep voids (d) TS of the same sample- near outer wall- absence of creep voids (e) TS of same sample -near the inner wall- isolated creep voids . **TS: transverse section**

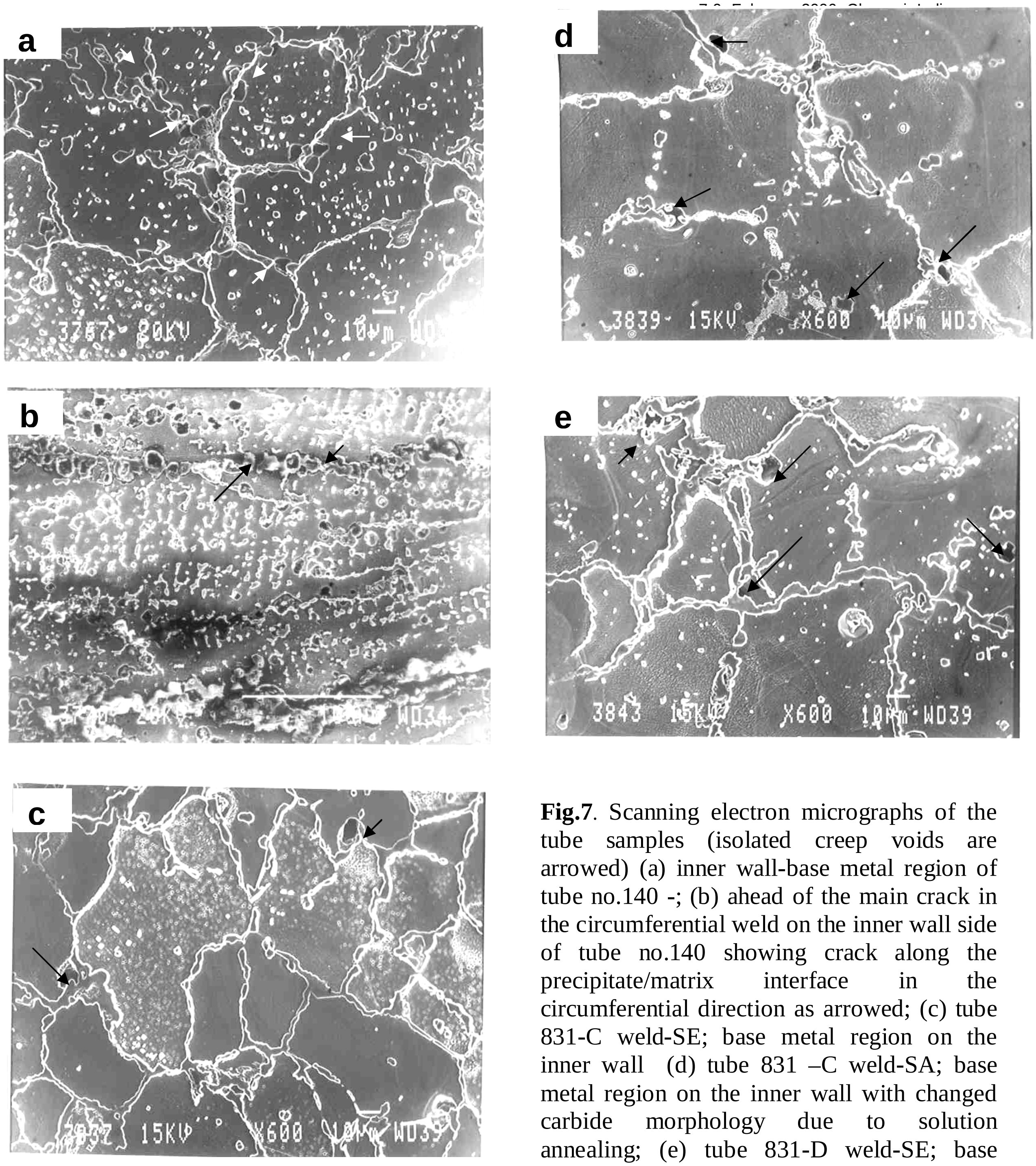


Fig.7. Scanning electron micrographs of the tube samples (isolated creep voids are arrowed) (a) inner wall-base metal region of tube no.140 -; (b) ahead of the main crack in the circumferential weld on the inner wall side of tube no.140 showing crack along the precipitate/matrix interface in the circumferential direction as arrowed; (c) tube 831-C weld-SE; base metal region on the inner wall (d) tube 831 –C weld-SA; base metal region on the inner wall with changed carbide morphology due to solution annealing; (e) tube 831-D weld-SE; base metal region on the inner wall