THE INFLUENCE OF MICROSTRUCTURE AND BIAXIAL STRESS ON CRACK PROPAGATION IN STEELS AS STUDIED IN SEM

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ABSTRACT

In the manufacture of pressure parts for high temperature steam applications, relatively thick boiler quality steel plates are fusion welded by electroslag welding and submerged arc welding. Amidst a vast majority of successful fabrication and welding programmes, a few problematic cases involving embrittlement of the materials were encountered. It was found that the characterisation of the material must be known in terms of interrelationship between microstructure and fracture processes as obtained by direct experimental data. With this in view a three point bending deformation stage of a notched or a precracked specimen with a metallographically etched surface was developed and utilized in SEM. The stress intensity factor and biaxial strains ahead of the crack can be determined. These methods have been utilized to investigate the relative cracking tendency of 127mm thick SA299 boiler drum plates of a particular steel maker after submerged arc welding. Similarly the failure of the transverse bend test specimens of submerged arc welded production test plates of SA515 Gr.70 supplied by one steel maker has been studied in detail. In both cases the present approach of analysing the micromechanics of deformation and fracture has led to better quality assurance.

KEYWORDS

Pressure vessel steels; high temperature service; fusion welding; embrittlement; notch bend specimens; deformation stage; scanning electron microscopy; microstructure; stress intensity factor; through thickness ductility.

INTRODUCTION

It is well known that a considerable improvement in fracture resistance of metallic materials can be achieved by controlling the micromechanics of deformation and fracture through a proper choice of microstructure. Sometimes the materials are found to have selective embrittlement over a narrow region, as typically seen near the fusion line of a weld with irregular contour and in a plate or a pipe with segregation. In this context it is difficult to conduct the standard plane strain fracture toughness test (which requires big specimens for low strength ferritic steels) and correlate the results with the localised changes in structure. Usually it is difficult and time consuming to correlate the deformation and crack propagation as related to microstructure when these studies are done independently. It is essential to combine the microstructural features and fracture characteristics in a suitable investigation procedure (Morton, 1977; Rosenfield, Hahn and Emburry, 1972; Venkataraman and colleagues, 1979, 1980). Thus in this paper an attempt is made to compare the biaxial deformation and fracture behaviour with the microstructural features of pressure vessel steels as applied to welding. For this purpose a SEM deformation stage for miniature notch bend specimens has been utilized. The specimen can be specially etched, fatigue precracked and bent to suit the experimental needs. This approach helped to understand the microscopic processes in crack initiation and propagation.

EXPERIMENTAL

The present method uses miniature notch bend (MNB) specimens which can be selected with the notch located at a localised region of interest (Fig.1). The SEM bending stage requires load versus load point displacement calibration of MNB specimen with or without a precrack. The notched specimens are tested in a standard 3-point bend testing machine with load and load point displacement data recorded on a X-Y recorder. The typical tracings are schematically shown in Fig.2 It has been found that the

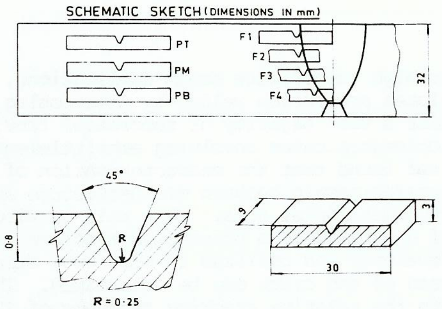

Fig.1 Schematic sketch showing the selection of MNB specimens from a welded plate; shaded region is polished and suitably etched.

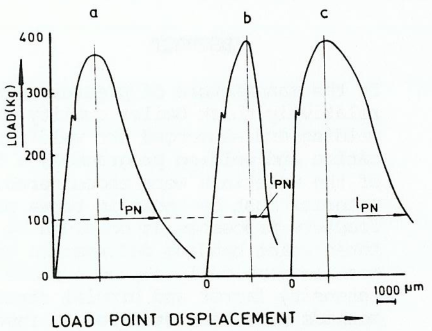

Fig.2 Load vs load point displacement sketches; a-parent metal; b-fusion line of plate PA; C-fusion line of plate PA-N; lpN - notch bend ductility.

arbitrary index of notch ductility lpN is closely related to ductility of production (code) bend test specimen (30 x 45 x 280mm unnotched). In order to simulate the surface biaxial and shear strain values of production test samples, a TEM square grid pattern of 130 x 130 μm is etched (Fig.3) on the metallographically polished surface (center of shaded area in Fig.1). The changes in dimensions of the grid at a localised region will give the information on localised biaxial and shear strain values. The grid etching is done by photoresist lacquer technique using TEM grid and 150W xenon arc light. After developing the photoresist lacquer the final etching is done by electrolytic etch using 1% nital. Subsequently the excess lacquer is wiped of with solvents such as chloroform or trichloroethylene. A further etching is also done to reveal structure on 80 x 80μm openings. This TEM grid etch technique gives reproduceable pattern which is ideally suitable for knowing the surface biaxial and shear strains at the root of a notch or a crack during bending.

After TEM grid etching, the MNB samples are fatigue precracked using special fixtures (Fig.4) in an Avery bending fatigue testing machine with facilities for measuring bending moment. For 45° V-notched bar, the bending moment My (Knott, 1973) to produce yielding is equal to $0.63\ \sigma_y\ (w-a)^2\ B/\ \sqrt{3}$. In the present case My = 4.65 N-m. The initial bending moment during fatigue precracking is maintained far below the value My, i.e. 2.0 - 2.5 N-m. After the generation of a crack the effective K values have been calculated by incorporating plastic zone correction (Pelloux, 1974; Hertzberg,

1976). The effective ΔK was about 20 MPa$\sqrt{m}$. Similarly the stress intensity values for different crack lengths have been determined. The SEM 3-point bending stage for MNB sample with or without precrack is utilized for monitoring the influence of microstructure and biaxial strain (stress) on crack propagation. The load can be increased upto 400 Kg by screwing the die steel screw. The span is 20mm for all tests. The displacement of load point is measured and the load is known from the calibration curve for the particular type of specimens . It is possible to observe the crack opening displacements (plane stress) with increasing load. After the complete fracture, the fractographic details due to slow bending is observed in SEM for correlating the earlier observations. Typical fractured samples show uniform length of fatigue precrack over two extreme levels (Fig.6). This is a valid point in the proper calculation of stress intensity factor.

The theoretical macroscopic deformation analysis of bend specimens with width/thickness ratio less than eight is difficult and hence practical estimations are recommended (Dieter, 1961). In the present case this value is 1.5 for the production (code) bend test specimen of size 30 x 45 x 280mm. Hence 4 x 4mm etched grid pattern on the face and side of the production bend test specimens helped in the analysis of biaxial and shear strains at various locations of 180° bend specimen (Fig.7) and notched specimen which developed crack after 30° bending. An attempt is made to obtain these surface biaxial strain conditions on TEM grid etched MNB specimens and subsequently observe the crack propagation behaviour. This approach has been helpful to analyse the failure of the production bend test specimens, for example the transverse bend test specimens (Fig.8) of fusion welded test plates attached to the longitudinal seam of pipes manufactured from rolled plates.

RESULTS AND DISCUSSION

Cold Cracking of Boiler Plate SA299

The cylindrical shells fabricated out of boiler quality plate SA299 supplied by steel manufacturers A and B were submerged arc welded with a preheat of 150°C. The dimensions of shells were Ø1800 x 127 x 5200mm. After the completion of welding several cracks as indicated by Magnetic Particle Inspection were noticed near HAZ in steel A whereas in steel B they were rare. Such types of cracks were frequently observed in steel A only.

TABLE 1 Chemical Composition of SA299 Plates

	C	Mn	Si	S	P	Cr	Mo	V	Ni
Steel A	0.27	1.32	0.27	0.010	0.013	0.20	0.10	0.05	0.1
Steel B	0.23	1.32	0.22	0.010	0.013	0.20	0.10	0.10	0.05
Spec SA299	0.31 max.	0.86 1.45	0.13 0.33	0.04 max.	0.035 max.				

TABLE 2 Mechanical Properties of SA299 Plates*

	Tensile test data Transverse				'Z'				Impact Energy, J at -25°C			Notch bend test lpN (mm)	
	YS	TS	%E	%RA	YS	TS	%E	%RA	L	T	Z	L	T
A	396	621	26	60	335	555	19	34	71	41	10	1.8	2.9
B	376	573	32	72	349	548	33	66	94	63	42	12.5	13.8

* Strength values in MPa; 2mm Charpy V for impact test.

The chemical composition and mechanical properties are respectively shown in Table 1 and 2. It is seen that Z direction ductility and impact toughness are poor in steel A. The microstructure of steel A indicated coarse bainitic bands which used to get preferentially hardened causing cold cracks. Slow notch bend tests of Charpy 2mm V notch on 7.8x11.8x55.0 samples indicated lower lpN value (Fig.2) in steel A compared to steel B.

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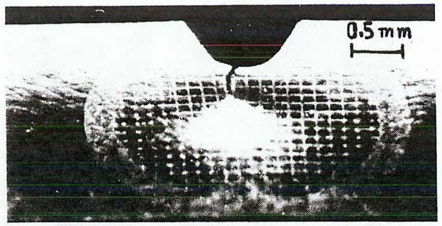

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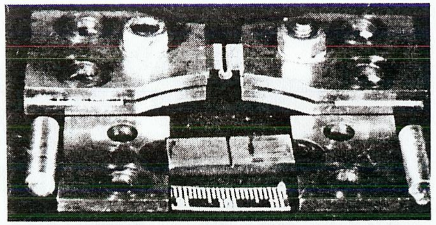

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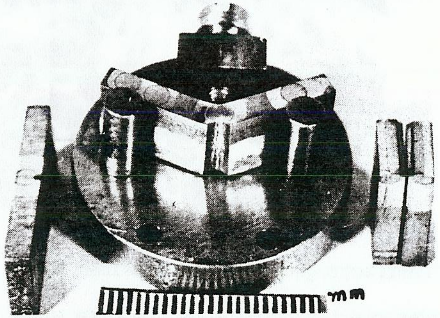

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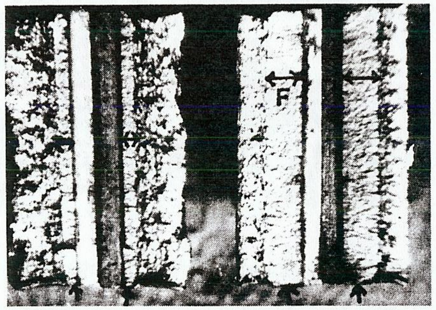

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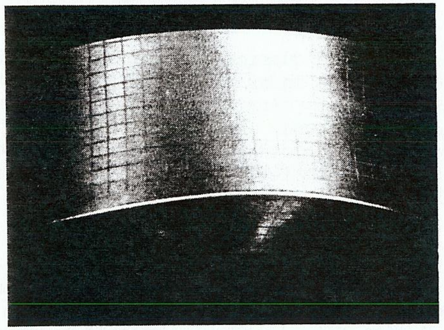

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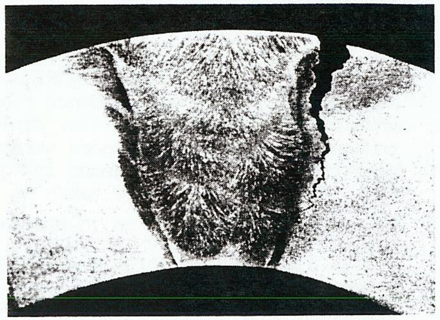

Fig.3. TEM grid etched pattern on MNB sample under load. Grid marked prior to precracking. Photo taken using stereomicroscope at 45° inclination to obtain the contrast of deformed region ahead of the crack.
Fig.4. Attachments for fatigue precracking of MNB specimens in Avery machine.
Fig.5. SEM deformation stage. Shows the bending of a grid etched specimen without precrack.
Fig.6. MNB specimen after fatigue precracking and bending, shows uniform length of fatigue precrack 'F' at two extreme levels.
Fig.7. Distortion of 4x4mm grid etched pattern on production bend test specimen after 180° bending.
Fig.8. Crack propagation near weld fusion line in a transverse bend specimen.

Since the material A is susceptible to cracking, the following investigation was carried out to check the fracture processes:
MNB specimens were prepared from both plates, and examined in SEM. Loads sufficient to initiate stable crack growth in specimens having 1.2 to 1.3 mm fatigue crack were applied for steel A and B in gradual sequences and the microscopic observations were made on a comparative basis. In steel A the size of plastic

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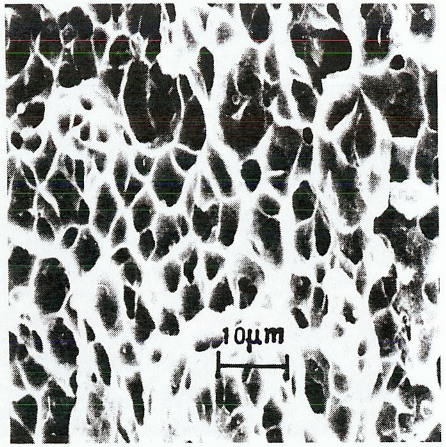
SEM PHOTOGRAPHS:
Fig.9. A network of cracking ahead of the notch of MNB specimen during loading.
Fig.10. Grain boundary cracking ahead of notch-Steel A.
Fig.11. Formation of heavy slip lines at a similar region ahead of the notch during loading of MNB specimen-Steel B (compare with Fig.10).
Fig.12. Quasicleavage fracture in steel A-fractograph of notched specimen after fracture by bending.

enclave (based on slip pattern development) ahead of the notch was smaller compared to steel B. Cracking over a wide area was noticed near the root for steel A (Fig.9). This feature continued to increase with increase of load. This region appeared to coincide with the location within the plastic zone (Fig.3) wherein the constraint is maximum due to biaxial stress (Garde & Weiss, 1972; Knott, 1973). In fatigue precracked specimens grain boundary cracking was observed very clearly (Fig.10) at a stress intensity factor of 27MPa $\sqrt{m}$ whereas in steel B even at higher stress intensity factors (e.g:55MPa$\sqrt{m}$) cracking was absent and extensive microscopic slip pattern with ductile voids was observed (Fig.11). The crack tip opening displacements were about



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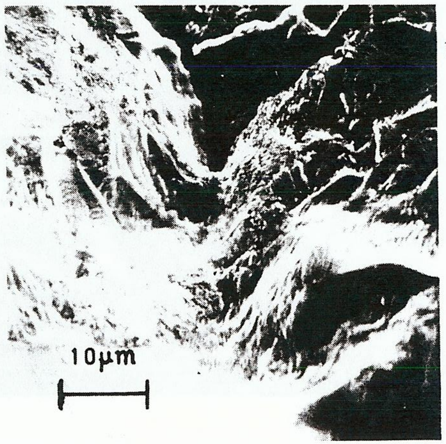

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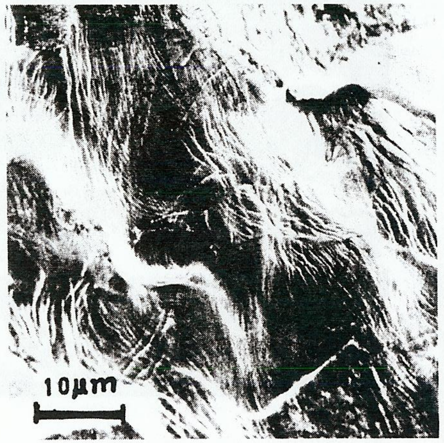

Fig.13. Dimple fracture in steel B under similar conditions-compare with Fig.12.
Fig.14. Fusion line region of SA515 Gr.70 (refer Fig.1) after loading. Absence of slip pattern and presence of cracks at C-Steel PA.
Fig.15. Extensive slip pattern and blunting of crack tip in steel PB near fusion line-compare with Fig.14.
Fig.16. Formation of multiple slip pattern in steel PA-N under similar conditions. Compare with Fig.14.

12µm and 40µm for steel A and B respectively under constant initial crack length and at the onset of stable crack growth. Ritter (1977) has excellently reviewed this aspect of stable crack growth and it has been shown that crack tip opening displacement $\delta = 4K^2/\pi\sigma_y E$ for the present situation. Good correlation has been observed between δ and K in the present experiment.

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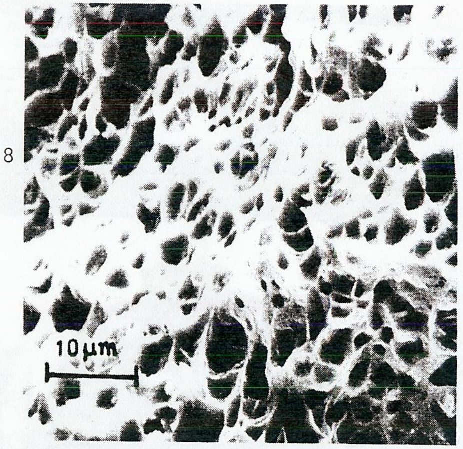

Fig.17. Quasicleavage fracture in steel PA-fractrograph of MNB specimen after bending.
Fig.18. Dimple fracture in steel PA-N under similar conditions, compare with Fig.17.

The fractograph after slow notch bend test revealed quasicleavage and dimple fractures in steel A and B respectively (Figs.12 and 13). But under tensile load both steels exhibited dimple fracture. Hence the constraint due to biaxial or triaxial stress induces embrittlement in steel A (i.e. stress induced fracture) whereas in steel B it is strain induced fracture. The banded structure of steel A could not be changed by practicable heat treatments. The reasons for grain boundary embrittlement is to be established by AES. Suitable steps were taken to eliminate cracks in material A.

Embrittlement of SA515 Gr.70 Plates

Amidst a successful large scale production of plateformed (using SA515 Gr.70) and submerged arc welded pipes, two melts of a particular supplier failed in the transverse bend test of production test plates (40mm) attached to the pipe (Venkataraman, Thyagarajan and Srinivasulu, 1980). The material PA failed even in repeated transverse bend tests with fracture occuring near the fusion line of HAZ (Fig.8). The chemical composition of this steel PA and a typical satisfactory steel PB are respectively 0.27 C, 0.26 Si, 0.82 Mn, 0.011 P, 0.023 S, 0.05 Al and 0.22 C, 0.23 Si, 0.81 Mn, 0.014P, 0.021 S. Further tests revealed low Z direction ductility (7% E, 10% RA) in steel PA when compared to steel PB which showed 23%E and 27%RA. Recent studies reveal that Hot Strain Embrittlement (HSE) could be one of the reasons for this type of problem in low alloy ferritic steels containing Aluminium (Kawaguchi and Arimochi, 1979). There are evidences for impurity segregation in 0.02% Al containing low alloy steels (Ericson, 1977) and reduction in COD values of the submerged arc welds obtained by using 0.03% Al containing steels. The solution to the problem was not reported.

TABLE 3 lpN Values of MNB Specimens* (mm)

Steel PA			Steel PB			Steel PA-N
PM		F	PM		F	F
T	2.3	0.9 (1)	T	3.9	6.8 (1)	6.0 (1)
M	2.5	0.7 (2)	M	3.8	6.2 (2)	5.2 (4)
B	3.5	0.7 (4)	B	3.8	5.4 (4)	

*Refer Figs.1 and 2 for meaning of abbreviations; PA-N is material PA after 920°C normalising.

MNB test data (Table 3) indicated low value of lpN for the fusion line of steel PA (Figs 1 & 2). The critical biaxial and shear strains of production bend specimens were obtained on MNB sample: longitudinal strain=0.30, lateral strain=-0.15 to -0.20 and shear strain =0.2 to 0.3. Under this condition the sample PA did not show significant slip pattern (Fig.14). Cracks were noticed ahead of the root. Whereas steel PB at similar location showed multiple slip pattern and blunting of crack tip (Fig.15). The samples PA after 920°C normalizing revealed multiple slip pattern at a similar strained region through better homogenization (as seen in Fig.16). The normalizing heat treatment cycle (1hr soaking per 25mm thickness) was implemented and the previously failed samples of group PA passed the 180° bend test without other adverse effects. The fractographs of steel PA and PA-N revealed quasicleavage and dimple fractures respectively (Figs.17 & 18) correlating the earlier observations. The stress intensity factor values of PA, PB and PA-N were respectively 23, 63 and 60 MPa$\sqrt{m}$ for stable crack growth of 1.2 mm in specimens precracked by fatigue. This indicates a definite improvement in fracture resistance of HAZ region in steel PA-N.

CONCLUSIONS

1. The present approach of microscopic observation of deformation and crack growth helped in the proper assessment of stress induced or strain induced fracture processes in pressure vessel steels.
2. The microscopic fracture process of SA299 plates of A series was mainly stress induced grain boundary cracking.
3. The failure of transverse bend specimens after submerged arc welding of SA515 Gr.70 test plates of steel PA was due to localized embrittlement. This was overcome by 920°C normalizing.

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