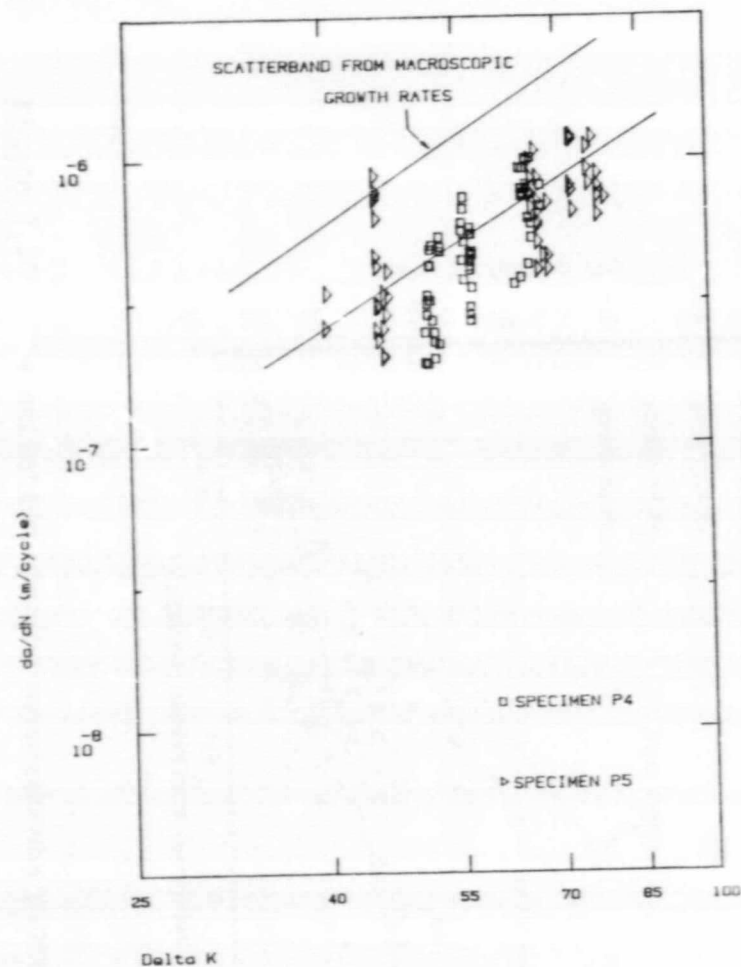


(a)



(b)

**Figure 7.29** Striation spacings plotted against  $\Delta K$  (a) W2 and W3 and (b) P4 and P5. The scatter band obtained in the macroscopic growth rates have been included on each graph.

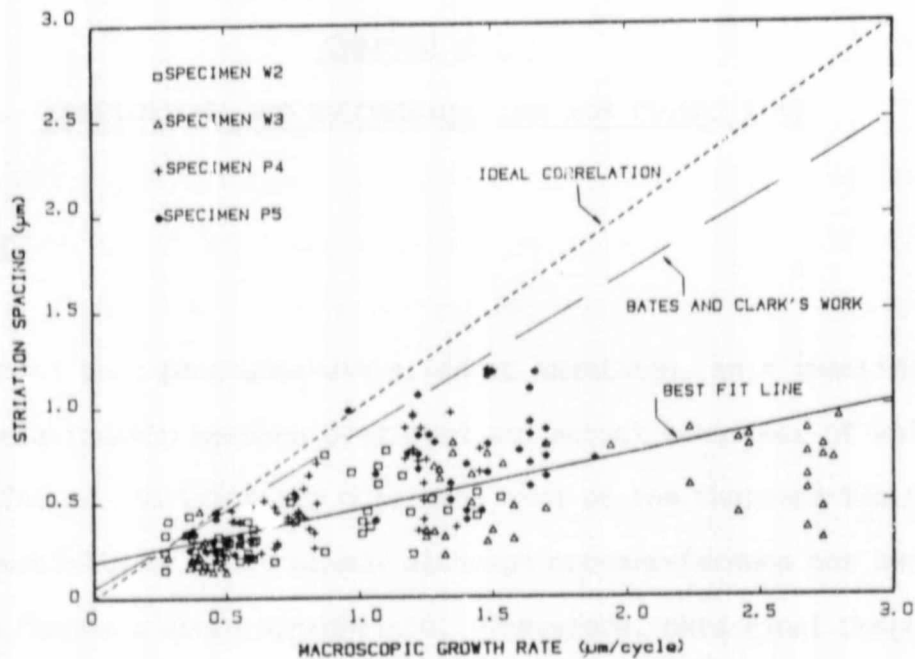


Figure 7.30 The striation spacing measurements plotted against the observed macroscopic growth rates. Note the large degree of scatter and the poor correlation between the two parameters.

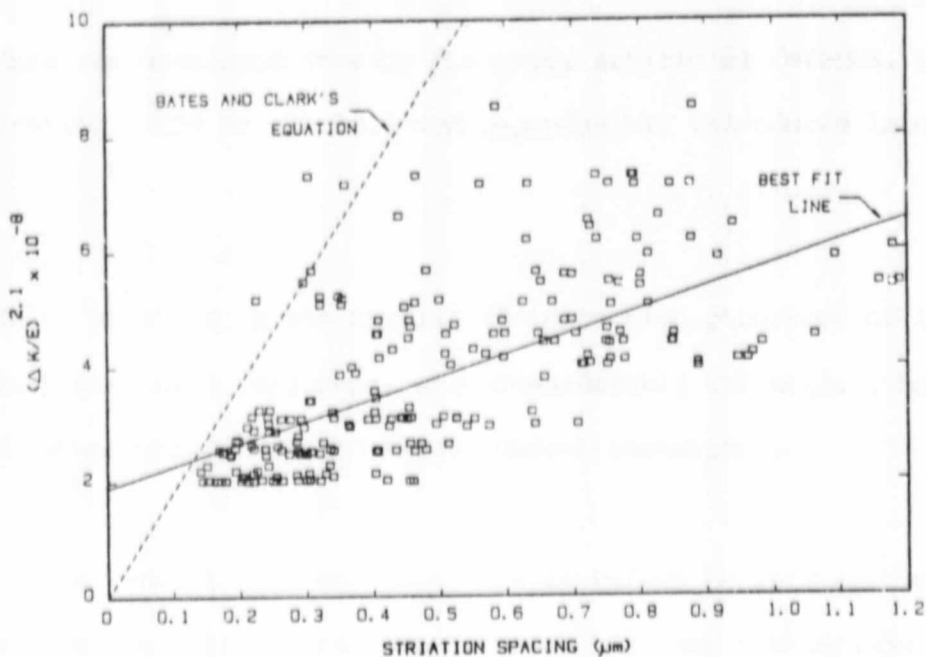


Figure 7.31 Striation spacing measurements plotted against the crack tip strain. Note that Bates and Clark's equation is not appropriate for these results.

CHAPTER EIGHT

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

8.1 Conclusions

This experimental test programme was aimed at examining, in a quantitative manner, the relationship between predicted and actual behaviour of welded joints containing defects. As initially outlined, each of the Chapters Two through Seven are essentially self-contained, although cross-reference has been made between these Chapters where appropriate. Therefore, this final Chapter - which serves to summarise the conclusions reached in each of these studies - is divided into six sub-sections, each detailing separately the conclusions of these preceding six Chapters.

8.1.1 Ultrasonic detection variability of weld defects

- (i) A procedure was developed whereby discrete, artificial defects, simulating lack of penetration could be reliably and reproducibly introduced into a set of weldments.
- (ii) The results obtained in the initial UT inspection programme of the thirty defective test plates were very poor, with considerable variability both between operators and between predicted and actual defect parameters.
- (iii) There was a general tendency to undersize defect heights and lengths. Defect depths were generally oversized, although this may have arisen due to the fact that the defect heights were undersized.
- (iv) No correlation was observed between operator experience and accuracy, although the operators with more than 20 years experience in this field tended,

on the whole, to be more consistently accurate than their less experienced counterparts. All operators, however, tended to underestimate their own errors.

(v) The nature of these artificial defects was such that it was possible for the single planar defect to appear as two isolated defects when performing an ultrasonic inspection of the weld. Having been instructed to size only one defect per test plate, the operator would then choose the larger of these two apparent defects, thereby considerably underestimating the actual defect height.

(vi) In the second UT inspection programme, far more accurate predictions of defect depths and heights were obtained. The results obtained in this inspection programme indicated that if a series of different sized defects were ultrasonically inspected, it would be possible to assess which of the defects was the most critical. Such accuracy however, is dependent on the operators being given sufficient background information about the component, and provided with a specific sizing procedure.

#### 8.1.2 Validation of analysis used in the PD 6493 and the R-6 defect assessment methods

(i) The results obtained in this sensitivity analysis, performed for both assessment methods, indicated that the proposed method of evaluating failure stress levels and defect criticalities are affected by variations in the input data. This analysis could therefore be used with confidence in assessing the effect of ultrasonic defect sizing variability on the fracture mechanics predictions.

(ii) It was shown how this type of sensitivity analysis could be used to determine structural stability under some pre-defined set of operating conditions, in addition to indicating critical conditions. Comparison of results obtained from both assessment methods would give added confidence in the analysis.

(iii) The sensitivity analysis performed for this work indicated that the stress-relieved MMA weld metal was the least defect tolerant in the PD 6493 approach. In the case of the Failure Assessment Diagram of the R-6 method, on the other hand, this particular material was the most defect tolerant. This anomaly arose due to the fact that there was no assessment of ligament stability for near-surface defects in the R-6 method; in addition, the stress-relieved MMA material had the highest flow stress, and therefore the lowest  $S_r$  parameter for a given defect size.

(iv) This type of sensitivity analysis could have particular application in the fabrication industry for optimising material selection, in addition to indicating whether or not a heat-treatment stress-relief would adversely affect the defect tolerance of a given material.

#### 8.1.3 The destructive testing of defective weldments

(i) Defective weldments were subsequently destructively tested under controlled four point bending conditions; twenty of the samples were tested in the as-welded condition, and ten in the stress-relieved condition. These results indicate that the welding residual stresses did not affect the recorded failure loads to any significant extent.

(ii) Comparing the recorded failure load for each specimen to that calculated from the actual defect parameters and using the Design Curve approach in BS PD 6493 indicated that the factor of conservatism inherent in this approach was about 2.

(iii) The relative defect criticality of the actual defect in each plate was assessed using the Failure Assessment Diagram of the CEGB R-6 document, and this indicated that the original R-6 Failure Assessment Line was somewhat conservative, and accordingly, modified Failure Assessment Lines were postulated

on the basis of the experimental results.

(iv) The results obtained from both UT inspection programmes were used as input data in the two fracture mechanics assessment procedures. Both BS PD 6493 and the CEEGB R-6 method exhibited some tolerance to the significant variability observed in the first UT inspection programme. The improved accuracy of the results obtained from the second UT inspection programme resulted in more precise estimations of the stress levels and defect criticalities.

(v) It was shown that the two assessment procedures were essentially compatible, with the UT defect which predicted the minimum failure stress level from the PD 6493 Design Curve being located in the critical region of the R-6 Failure Assessment Diagram, and the UT defect which gave the maximum failure stress prediction from the Design Curve being located in the safe region of the Failure Assessment Diagram.

#### 8.1.4 Fatigue strength of non-load-carrying fillet welds

(i) A high frequency test facility was established such that the influence of weld procedure and post weld dressing techniques on the fatigue behaviour of fillet welded specimens could be evaluated. This work essentially aimed at evaluating the 10 million cycle endurance limit of various balance pad weld details used in a particular type of all-welded steel centrifugal fan. (The endurance limit was defined here as the lowest stress range for which cracking did not occur within 10 million cycles.)

(ii) These results indicated that the revised, continuously welded detail had the same 10 million cycle endurance limit (50 MPa) as the original, non-continuous stitch-welded detail, due to the presence of short, sharp defects at the weld toe of the continuous weld. In the absence of any weld toe defects, the 10 million cycle of the continuous weld was 100 MPa.

(iii) A service fatigue failure was investigated, and it was found that the on-site welding, although appearing to be a continuous weld, had in fact been very poor with numerous undercut defects at the weld toe. Further, it was shown that the peak hardness of the near-heat affected zone was in excess of 400 Vickers microhardness. A test programme investigated this type of welding, and it was shown that the hard-near heat affected zone could combine synergistically with undercut defects to lower the endurance limit of the continuously welded detail to 40 MPa.

(iv) A series of tests were carried out at high mean stress levels in order to simulate the effects of welding residual stresses in the practical situation. These results indicated that any residual welding stresses that may be present in the fans would not affect the service fatigue behaviour.

(v) The preferential crack initiation sites in the continuously welded detail are easily removed by cost-effective techniques such as grinding and peening, and hence, specimens were supplied for testing that had been dressed after welding. The results of these tests indicated that the 10 million cycle endurance limit of the continuous weld could be increased to 160 MPa by grinding, and to more than 200 MPa by peening.

(vi) There were, however, instances where the dressing had not been effectively carried out, such that fatigue crack initiation occurred within a few million cycles of the starting stress range. It is therefore important that the practical implementation of these dressing techniques is not followed by an arbitrary increase in the operating stresses, without appropriate controls and periodic in-service inspections.

8.1.5 Crack initiation sites, crack shape development and crack growth rates

(i) Initiation typically occurred subsurface, at the weld root, in the stitch

welded specimens, although there were instances of crack initiation from the weld ends. No significant difference was observed in the initiation stress range for these two initiation sites. Cracking generally initiated from each corner of the balance pad and propagated into the load bearing plate on both sides of the attachment.

(ii) The presence of weld toe undercut was seen to cause a drastic reduction in the fatigue strength of the continuously welded sample. In the absence of undercut, initiation occurred at several points along the weld toe, as indicated by the presence of ratchet markings.

(iii) If the weld toe is effectively dressed, either by grinding or peening, the preferential crack initiation site is removed to the weld root, with a correspondingly higher endurance limit. However, some instances of weld toe initiation were observed in the dressed specimens and these served to indicate that some care and experimentation is required for the successful implementation of these dressing techniques. On the other hand, crack initiation could occur from the flame-cut edge of the load-bearing plate, remote from the dressed welds.

(iv) The change in crack front shape was monitored during the testing by heat-tinting or beachmarking. These results indicated that there was some variability in the early crack shapes, due to the different initiating defect shapes. However, the cracks tended to the semi-elliptical crack shape during propagation.

(v) Both the potential drop and the compliance methods were evaluated for use as crack monitoring techniques. However, it is necessary to mark the crack front in order to calibrate these indirect methods, and this affected the correlation between decrease in frequency (in the case of the compliance technique) and crack depth, or crack surface area. It was shown that the potential drop method cannot be easily applied to this specimen geometry, due to

the weld shape, and the fact that the initiation site is not precisely known at the start of the test.

(vi) However, the beachmarked specimens provided sufficient information for the evaluation of crack tip stress intensities and crack growth rates. It was shown that the cyclic stress intensity at the crack tip ( $\Delta K$ ) ranged between 5 and 30 MPa $\sqrt{m}$ , depending on the applied stress and the crack depth, and that this corresponded to rates of change of crack depth ( $da/dN$ ) of between  $3 \times 10^{-10}$  and  $7 \times 10^{-9}$  m/cycle. The rate of change of crack length ( $d2c/dN$ ) was shown to be an order of magnitude faster than the corresponding rate of change of crack depth ( $da/dN$ ).

#### 8.1.6 Fatigue striation spacings and macroscopic growth rates

(i) The macroscopic fatigue crack growth rates in parent plate and weld metal specimens were monitored using optical and electrical methods. The optical techniques characterised the propagation rate at the surface of the specimen, whilst the potential drop technique was seen to provide a total measurement of crack extension, inclusive of curvature.

(ii) The results of these tests indicated that there was some scatter in the measured crack growth rates; however, the three separate measurements gave compatible results. Some uneven crack growth was observed in one of the welded specimens, this being due to residual welding stresses; these are obviously not constant along the weld length, and therefore vary from specimen to specimen.

(iii) The fractographic examination of these fatigue-fracture surfaces was made difficult by the fact that the striations were not always well defined, and tended to occur in "packets". Both coarse and fine striations were found in close proximity to each other and, in some instances, the fine striations were seen to be sub-units of the coarse striations.

(iv) Striations could not be resolved in either the parent plate or the weld metal at cyclic stress intensities less than  $45 \text{ MPa} \sqrt{\text{m}}$ . At this level of applied stress intensity, the measured growth rates were  $5 \times 10^{-7}$  and  $1 \times 10^{-7}$  m/cycle for the parent plate and weld metal respectively.

(v) In a region where the macroscopic growth rate was measured to be  $1,20 \times 10^{-6}$  m/cycle, the coarse and fine striation spacing measurements indicated crack growth rates of  $1,24 \times 10^{-6}$  and  $4,66 \times 10^{-7}$  m/cycle respectively. Thus the coarse striations were seen to be more representative of the macroscopic conditions.

(vi) More generally, however, the striation spacings were seen, on the whole, to underestimate the actual fatigue crack growth rate, and this was particularly evident at the high stress intensities (greater than  $60 \text{ MPa} \sqrt{\text{m}}$ ). There were very few instances of the striation spacing overestimating the crack propagation rate.

(vii) At the higher growth rates (greater than  $2 \times 10^{-6}$  m/cycle), the striations were poorly defined and interspersed between regions of ductile void coalescence. Thus this "static mode" of fracture would have enhanced the local crack growth rate, and the striation spacing would obviously underestimate the optical or potential drop measurements of crack propagation.

(viii) When the striation spacings were plotted on a log-log scale against the applied cyclic stress intensity ( $\Delta K$ ), there was - apparently - good correlation with the scatter band obtained in the macroscopic crack growth rates recorded for the two weld metal specimens, up to a  $\Delta K$  level of  $70 \text{ MPa} \sqrt{\text{m}}$ . This agreement was in marked contrast to the very poor correlation observed between the striation spacing measurements and the macroscopic growth rates.

(ix) This data serves to illustrate the caution that must be observed when transposing striation spacing measurements onto the log-log  $da/dN$  versus  $\Delta K$

curve, since this may indicate a good agreement between striation spacings and macroscopic growth rates. The actual difference, however, becomes immediately apparent when these two parameters are directly compared on a linear scale.

## 8.2 Recommendations for future work

In many of the areas investigated in the experimental programme reported in this thesis the conclusions reached, and their inter-relationship with other literature, are relatively unequivocal. In other words it is submitted that many aspects covered are now terminally conclusive. However, there is one important area of which must justify further work and that concerns the correlation between fatigue striation spacings and the measured macroscopic growth rates. It will be recalled from Chapter Seven and Section 8.1.6 above, that the striation spacing measurements tended, on the whole, to underestimate the macroscopic growth rates, but that the striations were often poorly defined and located as packets. Therefore, the following experimental programme is proposed:-

- (i) Repeat of the fatigue test programme detailed in Chapter Seven, but using aluminium alloys, or austenitic stainless steels such that the striations are numerous, well defined, and therefore, easily measureable.
- (ii) Formulation of a mechanistic model for the formation of both coarse and fine striations, and the interrelation between these two. This will include examination of the "two-stage" striation model which proposed that, at low applied stresses, a number of cycles are required to accumulate sufficient strain at the crack tip before an increment of extension occurs.
- (iii) An examination of the correlation of striation spacing with the macroscopic growth rate at low, medium and high crack propagation

rates in these FCC alloys. This will include cross-correlations with the applied stress intensity, and the strain at the crack tip.

- (iv) Extension of this model to the low alloyed, ferritic steels and weld metal specimens used in this work. It is envisaged that replicating techniques will be implemented, such that the transmission electron microscope (TEM) may be used to improve the resolution of the striations found in these BCC metals.

In this way it is intended that the question of whether or not striation spacings can be used to estimate crack growth rates and (hence levels of applied stress) will be unambiguously answered for all common engineering metals.

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Nine Research Reports pertaining to work described in this thesis are used here as references: 62, 63, 66, 104, 106, 108, 109, 110 and 141.

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**Name of thesis** Fracture Mechanics Analyses Of Static And Dynamic Failures Associated With Welding. 1986

***PUBLISHER:***

University of the Witwatersrand, Johannesburg

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