A STUDY OF THE FATIGUE BEHAVIOUR OF BUTT WELDS MADE ON BACKING BARS

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The influence of the geometry of butt welds made on backing bars on their fatigue strengths under transverse loading was studied. Seven joint configurations in structural steel were fatigue tested. Agreement between the results and fatigue strengths calculated using fracture mechanics was reasonable. The comparison showed that the fatigue strengths of joints with the backing fillet welded to one plate were hardly affected by plate thickness (13-25mm) or a 2mm gap between the plate and backing. Fatigue strength was increased by tack welding the backing bar in position, but then unaffected by their shape and thickness. Fillet welding the backing to both plates produced a further increase in fatigue strength.

INTRODUCTION

There are many practical situations in which it proves necessary to make butt welds from one side only. For example, joints in tubular members and joints in plate structures where access to one side is difficult or prevented. Under transverse repeated loading, the fatigue strengths of such joints are critically dependent on the root condition and, to ensure that full root penetration is achieved, it is common practice to make the welds onto permanent backing bars. Such a method of construction might also be desirable as an aid to site assembly, for example when fit-up is poor.

There are three possible sites for fatigue cracking in transverse butt welds made on backing bars, as shown in Fig. 1. For fatigue failure from the butt weld toe, the fatigue strength of the joint would be similar to that of a butt weld made from both sides by the same process. However, the most likely mode of failure is by fatigue crack propagation from the weld root through the butt weld and in this case the fatigue strength is lower than that of a full penetration weld made from both sides. Similarly, if the backing bar is tack welded in position, fatigue failure from the toe of the fillet weld would result in a reduction in fatigue strength as compared with that of the butt weld made from both sides. Some fatigue design rules for welded steel structures (e.g. BS5400 for bridges, BS6235 for fixed offshore structures in Britain) already include butt welds made on backing bars. For failure from the weld root through the butt weld they fall into Class F in the British rules, the same class as that for fillet welds failing from the weld toe. This reflects the

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relatively severe stress concentration associated with the butt weld root. However, fatigue test data for the joint are widely scattered suggesting that some distinction between different joints might be possible on the basis of geometric differences. If this is the case, their may be scope for optimising the fatigue strength of the detail by suitable choice of geometry and therefore increasing its classification in the fatigue design rules. Therefore, the present study of the effect of some geometric variables on the fatigue strengths of transverse butt welds made on backing bars was carried out. The study was based principally on comparative fatigue tests carried out on butt welds made in a structural steel but, in addition, theoretical analyses were performed using fracture mechanics to investigate how successfully the influence of geometric changes could be predicted.

LITERATURE SURVEY

The design S-N curve for transverse butt welds on backing bars in the British rules was selected on the basis of two sets of published data (1, 2), as shown in Fig. 2. In both cases the tests were carried out under axial pulsating tension loading (stress ratio R = 0) on 13mm thick specimens. The low classification of the joint arises largely because of the results obtained by Newman and Gurney (1) who tested manually welded mild steel specimens with 3mm thick backing bars not fillet welded in position. Konishi (2) tested joints in structural carbon manganese steel welded manually or by submerged arc with 9mm thick backing bars fillet welded into position. The welds were intended to simulate those likely to be produced in steel bridge construction and one series of specimens was made with a 2mm gap between the backing bar and plates to simulate the poor fit-up likely to be experienced in site welds. Also shown in Fig. 2 are two series of results produced under the same loading conditions since the design rules were published (3, 4). Larionov (3) tested 20mm thick specimens while those tested by Maddox (4) were 12mm thick with 6mm thick backing bars which were not fillet welded into position. In both cases structural carbon manganese steel was used and the welds were made manually. The recent results tend to be slightly lower than those obtained by Konishi but they do not change the calculated mean S-N curve and confidence limits significantly. The mean S-N curve and 95% confidence limits to all the data are included in the figure; the lower 95% limit virtually coincides with the Class F design curve.

The results in Fig. 2, which embody a number of geometric variables, were examined with a view to identifying which features contribute to the low fatigue strength of some transverse butt welds on backing bars. However, none was obvious. First, both manual and automatic submerged arc welds are covered and on the basis of the results obtained by Newman and Gurney (2), which were consistently low, it might be concluded that automatic welds give higher fatigue strengths than manual ones. However, the highest fatigue strengths obtained by Konishi were from manual welds, all results falling above the mean S-N curve, while some results from submerged arc welds fell below the mean. Another feature which might be expected to reduce fatigue strength is poor fit between the backing bar and plates but, again considering Konishi's results, a gap of up to 2mm did not produce a consistent indication of reduction in fatigue strength. A striking difference between the Newman and Gurney specimens and the others was the use of a very thin backing bar, only 3mm thick, which was not fillet welded into position. However, since the load attracted by the backing bar is likely to be lower in this case than when a thicker backing bar is fillet welded in position, it is difficult to see how these

features might explain the fact that the fatigue strengths of their specimens were consistently low. Finally, Larionov tested relatively thick specimens and their generally lower fatigue strength might be attributable to this fact, other work having shown that an increase in plate thickness might lead to a reduction in fatigue strength, as discussed by Gurney (5).

One aspect of the test results given in Fig. 2 which will not be pursued in the present paper concerns the influence of residual stresses. It will be observed that the S-N curves for some individual test series appear to be considerably shallower than the S-N curve produced by an analysis of all the results together. As discussed by Maddox (6), compressive residual stresses are likely to arise in the region of the root of butt welds made on backing bars with the result that fatigue strength tends to be increased, as compared with joints containing tensile residual stresses, and the S-N curve is shallower.

The influence on the fatigue strengths of butt welds made on backing bars of the geometric variables discussed above were considered further in the present work. In view of the influence of residual stresses, attention was confined to the behaviour of stress relieved joints.

TABLE 1 Details of fatigue testing programme.*

Specimen type	Test series no.	Plate thickness, mm	Details of backing system
A	1	13	8mm thick steel, fillet welded to one plate
A	2	25	8mm thick steel, fillet welded to one plate
A	3	13	8mm thick steel, 2mm gap between backing and main plates, fillet welded to one plate
B	4	13	8mm thick steel, tack welded at root
B	5	13	5mm thick steel, tack welded at root
B	6	13	Half-round steel beading, tack welded at root
C	7	13	8mm thick steel, fillet welded to both plates

* All specimens stress relieved and tested under pulsating tension loading (R = 0)

TEST PROGRAMME

The programme consisted of seven series of fatigue tests on three basic types of butt welds made onto backing bars under transverse loading. Details of the specimens are shown Fig. 3 while some details of the various test series are given in Table 1. The geometric variables studied in Type A joints, in which the backing bar was fillet welded into position, were main plate thickness (13 or 25mm) and the presence of a gap of up to 2mm between the backing bar and plates to simulate poor fit-up. Type B joints were designed to investigate the fatigue strength of joints made onto backing bars which were not fillet welded in position. Two thicknesses, 5 and 8mm, of steel backing bar were tack welded to the edge of one plate prior to welding while the half round steel beading backing strip was clamped into position. The thin backing bars are of particular interest because the lowest results in Fig. 2 were obtained from similar details. The clamped backing bar is sometimes used for making site welds. Although the fillet welding of the backing bar to one of the plates to be joined may be useful as an aid in the setting up and alignment of the joint prior to butt welding, a disadvantage for site welded joints is that unless the fillet welding is carried out immediately before butt welding, corrosion readily occurs in the crevice between the backing bar and plate and leads to porosity in the subsequent butt weld. Finally Type C joints were made onto 8mm thick backing bars which were first fillet welded to both plates. Such joints are of practical interest since they may be used to make site welds when fit-up and alignment between the two plates is poor.

EXPERIMENTAL DETAILS

The test specimens were all made from structural carbon manganese steel which met BS4360 Grade 50B specification (minimum properties: yield strength 345N/mm^2, ultimate tensile strength 490N/mm^2, elongation 18%). The butt welds were made by submerged arc welding onto steel backing bars which were fillet welded to one or both plates or tack welded to the edge of one plate, as detailed in Table 1. Tack welds at the edge were subsequently remelted and buried when the butt weld was made.

The welds were made between steel plates 1200mm wide by 450mm long and the joints were subsequently sawn into 150mm wide specimens. The specimens were straightened and then thermally stress relieved by heating them in the range 580-620°C in a furnace for one hour. The corners and edges of the specimens were ground smooth.

The specimens were tested axially under pulsating tension (stress ratio R = 0) at frequencies in the range 5-16Hz. Misalignment and lack of symmetry in the specimens meant that secondary bending occurred and therefore when this was significant actual stresses in the region of the weld were measured using 5mm gauge length electrical resistance strain gauges.

FATIGUE TEST RESULTS

The fatigue test results are plotted in terms of the average stress on the main plate in Figs 4-8. As expected, Types A and B joint normally failed as a result of fatigue crack propagation from the root through the butt weld, but in one case failure was from the butt weld toe. In Type C joints the stress at the butt weld root would be lower than that in Type A and B

joints due to the reinforcement provided by the fillet welded backing bar. Thus, not surprisingly, failure was transferred to the fillet weld toe.

For comparison with published data, all the results for joint Types A and B are plotted together in Fig. 9 with the mean and 95% confidence limits for the data in Fig. 2. As will be seen, most of the present results lie below the mean and therefore add support to the choice of design class for this weld detail. However, there are differences between the results, in particular Type B joints (tack welded backing bars) tending to give higher fatigue strengths than Type A (fillet welded backing bars). In order to determine whether or not such differences reflect the influence of geometric variables or are simply due to scatter from one weld series to the next, fracture mechanics was used to analyse the fatigue behaviour of all the joint types tested.

FRACTURE MECHANICS ANALYSIS

Method of Analysis

Fracture mechanics was used to calculate the fatigue strengths of all the joint types for the two main modes of fatigue failure experienced. The basis of the analysis was the fatigue crack propagation relationship (Paris' law) for the material:

$$\frac{da}{dN} = C(\Delta K)^m \qquad (1)$$

where C and m are material constants, da/dN is the rate of crack propagation and ΔK is the stress intensity factor range. ΔK may be expressed:

$$\Delta K = Y\,\Delta\sigma\sqrt{\pi a} \qquad (2)$$

where $\Delta\sigma$ is the applied stress range, 'a' is the current crack length and Y is a function of the geometry of the crack and the cracked component. Assuming that the fatigue life of the weld detail consists mainly of the propagation of a pre-existing flaw, as is thought to be the case (7), equation 1 can be used to calculate the life by integration. Thus, rearranging equation (1) so that all the terms which depend on 'a' are together,

$$\frac{da}{(\Delta K/\Delta\sigma)^m} = C\,\Delta\sigma^m\,dN$$

and

$$\int_{a_i}^{a_f} \frac{da}{(\Delta K/\Delta\sigma)^m} = C\Delta\sigma^m N \qquad (3)$$

where N is the number of cycles required to propagate the crack from a_i to a_f. If a_i is the size of the inherent flaw and a_f is the crack size at failure, N is the fatigue life for applied stress range $\Delta\sigma$. Clearly, equation 3 could represent the S-N curve for the geometry considered, such that

$$\Delta\sigma^m N = A = \frac{I}{C} \qquad (4)$$

I being the crack propagation integral and A the constant which defines the position of the S-N curve.

Stress Analysis

In general, the term Y in equation 2 depends on the crack size and position, in relation to free surfaces, and the crack front shape. For crack growth from the root of a butt weld or from a fillet weld toe, it is also influenced by the stress concentration in the region of crack initiation, an influence which dies away as the crack propagates away from that region, (8). In the present case, for cracks within the region of influence of the stress concentration Y was determined for the seven joint geometries using a 2D-finite element stress analysis program developed by Smith (9). Such solutions are applicable to straight-fronted cracks propagating uniformly across the stressed section. In practice, although crack initiation was reasonably uniform across the specimen width, the fatigue cracks adopted semi-elliptical crack front shapes. It is possible to correct for this (8) but in the present case the crack depth to surface length ratios were so small, usually around 0.05, that the correction has negligible effect on the fatigue lives calculated. Therefore, the cracks have been assumed to be straight-fronted. In general, this is the most conservative assumption to make in circumstances in which the crack front shape is unknown. For crack growth beyond the region of influence of the stress concentration, the published solution due to Gross et al (10) for Y was used. The resulting relationships between $\Delta K/\Delta\sigma$ and 'a' are shown in Fig. 10 while Fig. 11 shows the corresponding relationships between $\Delta K/\Delta\sigma\sqrt{\pi a}$, that is the geometric function Y in equation 2, and a/B, where B = plate thickness. As will be seen, the variations in backing bar thickness and shape considered for Type B joints had no effect on ΔK and thus the five curves shown in Figs 10 and 11 cover all seven geometries considered.

The shapes of the curves in Fig. 10 were as expected. They would meet the ordinate for a/B = 0 at a value corresponding to the elastic stress concentration factor for the region considered but this information was not obtained in the present analysis. The characteristics of the ($\Delta K/\Delta\sigma$) v 'a' curves, Fig. 10, were also as expected, apart from those for Type A joints without a gap between the backing bar and plates. Normally, ΔK increases with increase in crack length but here in the early stages of crack growth ΔK decreases with increase in crack length for a period. These solutions were checked and confirmed. They imply that the influence of the relatively high stress concentration in these geometries decreases very rapidly as crack growth occurs, so that Y decreases more rapidly than $\sqrt{a}$ increases. It is not known why this same high stress gradient was not present in the other geometries containing butt weld root cracks.

Fatigue Analysis

Assuming that the geometric variations considered have no effect on the crack propagation characteristics of the material and that the weld metal and parent plate have similar crack propagation characteristics, which is

reasonable (11), the values of m and C in equation 3 can be assumed to be the same for all the geometries and crack sites considered. Another condition for making this assumption is that the residual stresses in the regions of cracking are such that they have the same effect on rate of crack growth in all geometries. In the present case this condition is met because all the specimens were stress-relieved. It will also be a reasonable assumption to make in practice on the basis that real structures will be assumed to contain the most detrimental residual stresses, that is high tensile residual stresses, in all regions of potential fatigue crack initiation in welded joints.

Fatigue crack propagation data for steels (e.g. Maddox (11)) suggest that m should be somewhere between 2 and 4. A value of m = 3 is usually chosen for high tensile mean stress conditions, as are assumed to exist in as-welded joints, and a value of m = 4 has been recommended for stress-relieved joints in the British code BS PD6493 (12). In the present case, a value of m = 3.5 seems appropriate since, from equation 3, it predicts a $\Delta\sigma$ v N relationship (i.e. S-N curve) of slope m = 3.5 which is similar to the slope of the mean S-N curve actually obtained for Series 1 (see Fig. 4), the series containing the largest number of results. As will be seen later, it is also a reasonable slope for the S-N curves for the other test series. The method used to decide on a value for C is described later.

A final assumption concerns the condition of the regions where fatigue cracking initiates, that is the butt weld root and the fillet weld toe. It is well-known that small sharp flaws are an inherent feature of weld edges and that fatigue cracks propagate from them (13). In the present analysis it will be assumed that such flaws are present at both crack initiation sites considered and that their depths are the same for all geometries. In practice, their depths will vary even for a given geometry, typically from 0.1 to 0.4mm at weld toes. Examination of the fracture surfaces produced from the present specimens which failed from the butt weld root indicated that defects, usually in the form of lack of penetration, of the order of 0.25mm deep provided the sites for fatigue crack initiation. Therefore, in the analysis, an initial crack depth of 0.25mm was used to consider both failure modes considered.

Thus, the present comparison of fatigue strengths reflects only the variation in stress concentration in the region of crack initiation and its effect on the stress intensity factor for a crack propagating from that region.

The crack propagation integral I in equation 3 was evaluated for the five $\Delta K/\Delta\sigma$ v 'a' relationships, assuming a_i = 0.25mm and a_f = 0.8B. The choice of value for a_f is not critical; in the present case most of the fatigue life was consumed by the time the crack tip was outside the zone of influence of the stress concentration, when a ~ 3mm, reflecting the well known fact that in most circumstances fatigue cracks in welded joints are relatively small for most of their lives because of the small sizes of the initial flaws and the exponential nature of fatigue crack growth rate. The integrals are given in Table 2. From equation 4, A is directly proportional to I, so that the higher the value of I, the higher the fatigue strength of the joint. On this basis, the results in Table 2 are listed in order of increasing fatigue strength.

In order to facilitate a comparison of the theoretical rating of the joints and the actual results, predicted S-N curves can be plotted using equation 4 if C is defined. This can be done using the actual S-N curve for one joint type on the basis that the S-N curve can be predicted accurately from equation 4. As before, the Series 1 results are used (see Fig. 4), for which the mean S-N curve (adjusted slightly to give m = 3.5) is

$$(\Delta\sigma)^{3.5}N = 1.9 \times 10^{13} \quad (5)$$

The fracture mechanics analysis gave I = 0.040 for this joint, so that

$$C = \frac{I}{A} = \frac{0.040}{1.9 \times 10^{13}} = 3 \times 10^{-15}$$

The line corresponding to this value of C is plotted in Fig. 12 together with the scatterband enclosing fatigue crack growth data obtained from a number of steel weld metals, heat affected zones and parent plates (11), for comparison. The deduced crack growth rate is seen to be exceptionally low, the line lying on or below the lower limit to the published data. A possible explanation for this is that the crack growth rate in the present specimens was actually higher than the deduced value and that a significant part of the fatigue life was spent initiating a crack. To check the deduced crack growth law, attempts were made to measure crack growth rate in some of the Series 1 specimens. The method used was to mark the fracture surface at intervals during the life, by applying soap solution to stain it and by reducing the cycling frequency for short periods. Limited data were obtained for crack depths down to 0.5mm and the results, analysed in fracture mechanics terms are included in Fig 12. As will be seen, there is good agreement between the actual and calculated crack growth rate, confirming that the deduced crack growth law is reasonable.

Assuming from equation 4 that A = I/C and using the appropriate value of I from Table 2, values of A for the other joint geometries were calculated and they are included in Table 2. The corresponding predicted S-N curves are compared with actual test results in Figs 4-8.

TABLE 2. Results of fracture mechanics fatigue analysis.

Joint Type	Test Series	Crack propagation integral, I	Calculated S-N curve $S^{3.5}N = A$
A	1	0.040	1.9×10^{13} *
A	2	0.049	2.3×10^{13}
A	3	0.053	2.5×10^{13}
B	4-6	0.066	3.15×10^{13}
C	7	0.121	5.75×10^{13}

* Reference value from which C was deduced and other values of C subsequently calculated using A = I/C

DISCUSSION

Bearing in mind that some variation in fatigue strength from one test series (and hence weld) to another is to be expected, the agreement between actual and calculated fatigue lives in Figs. 4-8 is seen to be good. This suggests that, as far as the general behaviour of the test specimens was concerned, the assumptions made in the fracture mechanics crack propagation analysis were reasonable. The crack growth law was confirmed by limited test data but the possiblity cannot be ruled out that fatigue crack initiation was significant in some specimens since many gave lives well above the predicted mean S-N curve. However, it can also be argued that the higher lives are attributable to the presence of inherent flaws which were smaller than that assumed, so that crack growth life was actually greater than that calculated for a_i = 0.25. Whatever the explanation for the longer lives, the good correlation between the actual and calculated mean S-N curves indicates that the variations in fatigue strength observed for the three types of joint can be attributed mainly to geometric variations. In view of this, a number of conclusions can be drawn.

First, considering the two thicknesses of Type A joint, even though $\Delta K/\Delta\sigma$ was higher in the thicker joint for very small crack depths, the position was reversed for deeper cracks and, overall, for the initial crack depth considered, the fatigue lives were predicted to be similar, as found in the fatigue tests. Thus, the detrimental effect of increased plate thickness seen in some fillet welded joints (5) does not arise in the butt welds made onto permanent backing bars considered here, at least up to 25mm thickness. It is probably significant that the thickness effect observed in fillet welded joints is closely linked with the overall geometry of the joint, particularly the size of the 'attachment' to the plate in which fatigue cracking occurs, and is strongest when the 'attachment' size is scaled up with plate thickness (14). In the context of the present joint, weld width at the root would seem to be the only relevant 'attachment' size but this is unlikely to increase in proportion to plate thickness.

Secondly, the analysis predicted that the presence of a gap between the backing bars and plates, intuitively a bad feature, would not reduce fatigue life and the present test results and results in the literature (2) support the prediction. From the practical viewpoint this means that the fatigue strength of the joint is very tolerant to poor fit-up, as long as penetration of the butt weld to the backing bar is achieved.

Thirdly, the analysis indicated that the type and thickness of the backing bar in Type B joints had no effect on fatigue strength. The test results were scattered but, at least for Series 8 and 9, generally supported the analysis. However, the test results for Series 10 joints, made onto half-round beading, suggested a slightly higher fatigue strength for this joint. A possible explanation for this is that the initial defect depth was less in the Series 10 specimens than in the Series 8 and 9 specimens, due to the natural variation that would be expected to arise from one welding procedure to another. The fact that the absence of a fillet weld attaching the backing bar appears to improve the fatigue strength of the joint suggests that an increase in the design class might be justified. However, as seen in Fig. 9 the results are still relatively low compared with published data and clearly such an increase is not justified.

Fourthly, considering the Type C joint, it was rather surprising to find both experimentally and theoretically that their fatigue strengths were much higher than for the other joints. Normally, fillet welded attachments to stressed plates which fail by fatigue crack growth from the weld toe have fatigue strengths similar to or lower than butt welds made on backing bars (6). However, the finding is compatible with the fact that Type A joints with fillet welded backing bars invariably fail in the butt weld from the root, rather than from the toe of the fillet weld, which implies that the butt weld root represents the more severe stress concentration.

The present results demonstrate one of the most valuable applications of fracture mechanics analysis, namely for studying the effect of geometric variables on the fatigue strength of a particular type of welded joint for which some fatigue data are available. The reference data are necessary to provide the means of checking that reasonable assumptions have been made about the constants in the Paris law and the size of inherent defect from which fatigue cracks will propagate. It is envisaged that such analyses will prove to be useful for justifying whether or not particular variations in geometry (e.g. plate thickness, attachment size or shape, weld profile) are likely to change the design S-N curve for the weld detail without the need for extensive fatigue testing. Alternatively, the method could be used to determine what geometric changes will lead to a particular change in fatigue strength, such as a drop from one design class to another. At present British design rules embody some distinction between fillet welded joints on the basis of the attachment size but the distinctions are somewhat arbitary and do not consider the inter-relation of attachment size and plate thickness. Fracture mechanics can be used to clarify this situation. It is hoped that the good agreement between actual and calculated fatigue strengths found in the present study will increase confidence in the application of this technique.

CONCLUSIONS

Based on fatigue tests of butt welds in steel plates made onto permanent backing bars carried out under axial pulsating tension loading (R = 0) and theoretical analyses using fracture mechanics, the following conclusions were drawn:

a) Reasonable correlation between actual and calculated fatigue lives is obtained on the basis that the fatigue life consists entirely of the growth of a pre-existing crack-like flaw.

b) The fatigue strengths of butt welds made onto backing bars fillet welded to one plate were similar for plate thicknesses of 13 and 25mm. The presence of a 2mm gap between the backing bar and plate, representing poor fit-up, did not affect fatigue strength.

c) The fatigue strength of butt welds made onto three types of steel backing bar, 5 and 8mm thick plate and 6mm thick half-round beading, which were not fillet welded in position, were similar and slightly higher than that for joints with fillet welded backing bars.

d) Attachment of the backing bar to both plates transferred failure to a fillet weld toe and led to a further increase in fatigue strength.

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SYMBOLS

a	= crack depth, measured in direction of crack growth (mm).
a_i, a_f	= initial and final crack depths (mm).
A	= constant in equation for S-N curve.
B	= plate thickness (mm).
C	= constant in crack growth relationship (Paris' law).
$\frac{da}{dN}$	= crack growth rate (mm/cycle).
ΔK	= stress intensity factor range ($Nmm^{-3/2}$).
$\Delta\sigma$	= stress range (N/mm^2).
I	= crack propagation integral.
m	= index in Paris' law and S-N curve equation.
N	= fatigue life (cycles).
Y	= function to 'correct' ΔK for geometry of cracked component.

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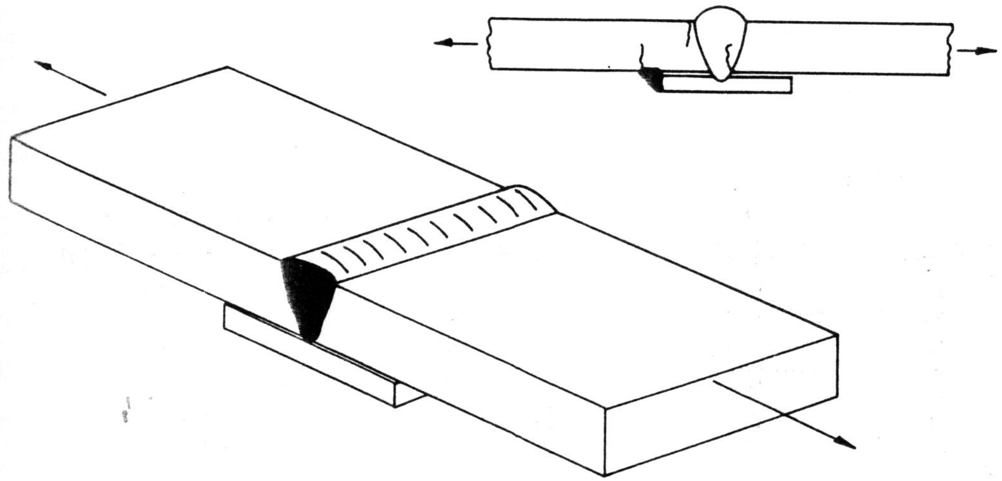

Fig. 1. Modes of fatigue failure in transverse butt welds made on permanent backing bars.

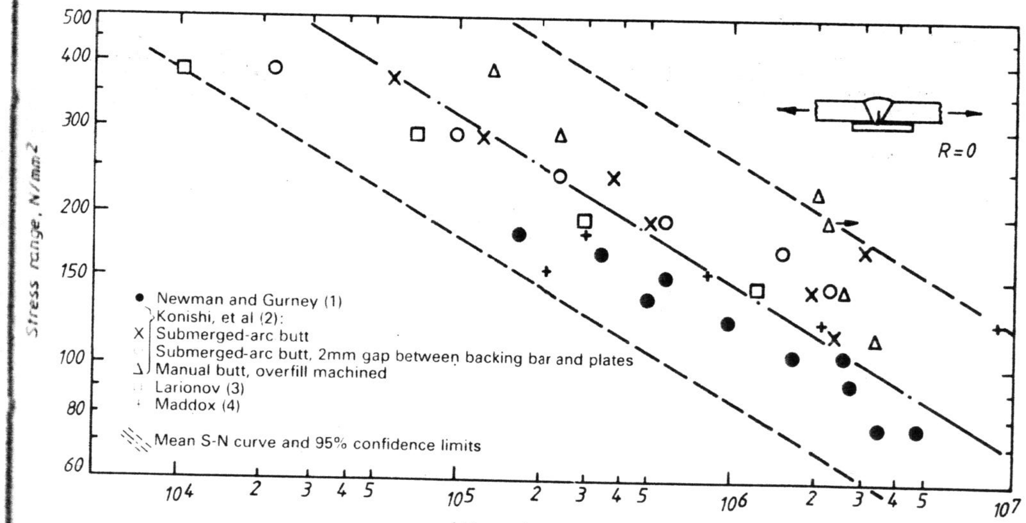

Fig.2. Fatigue test results obtained from transverse butt welds made on a backing bar.

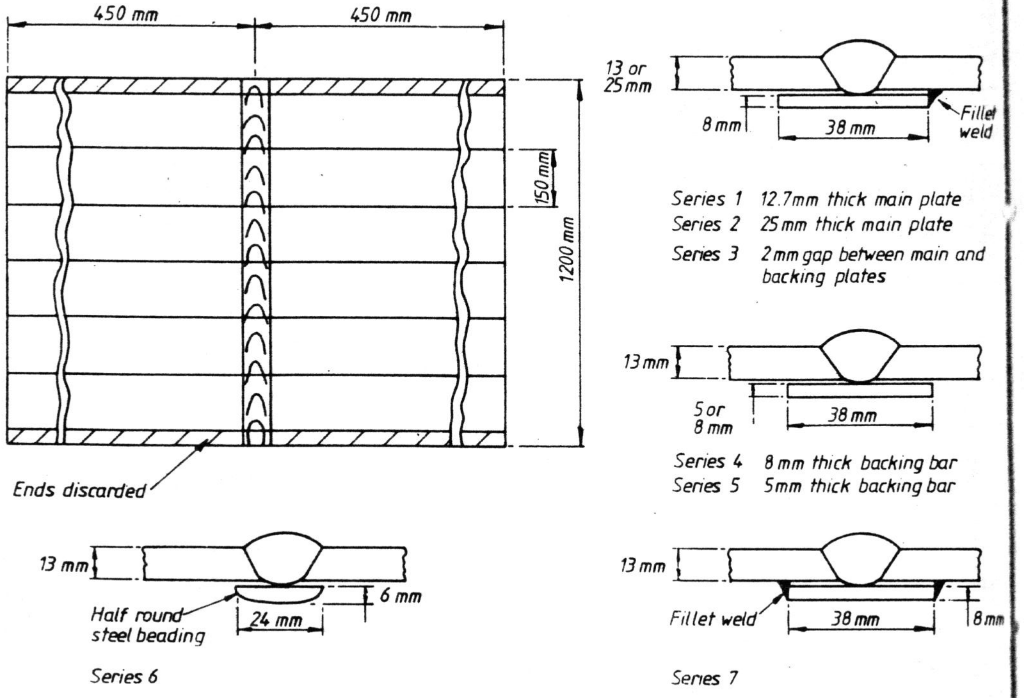

Fig.3. Details of test specimens.

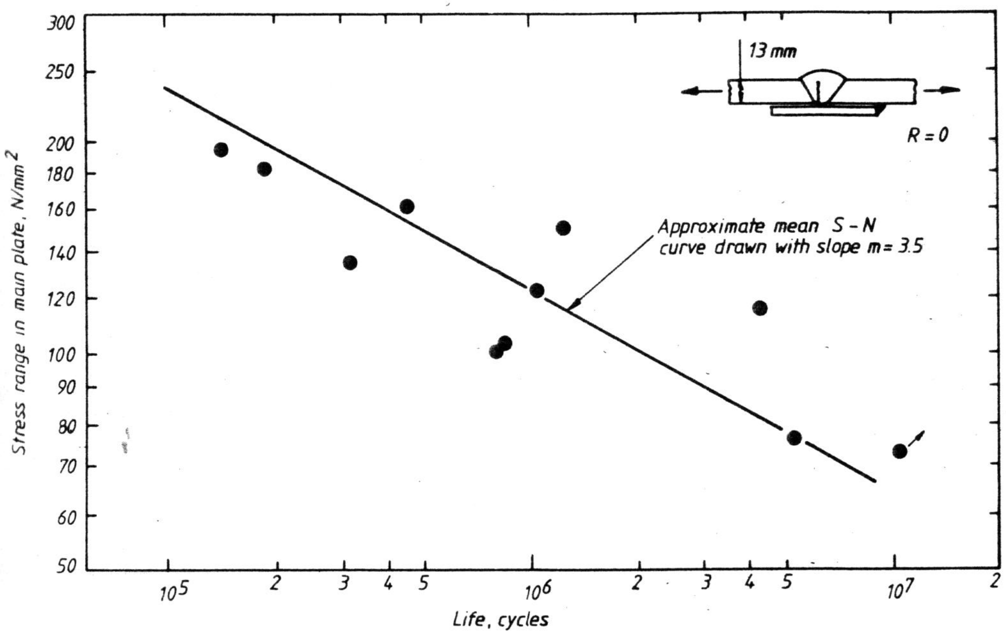

Fig.4. Fatigue test results for Type A Series 1 (13mm thick) specimens.

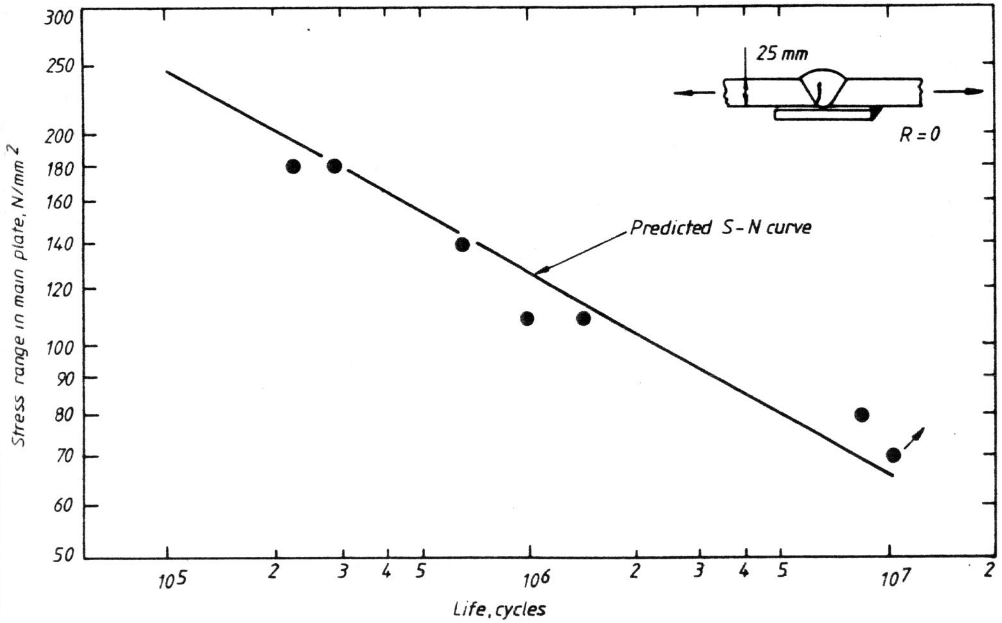

Fig.5. Fatigue test results for Type A Series 2 (25mm thick) specimens.

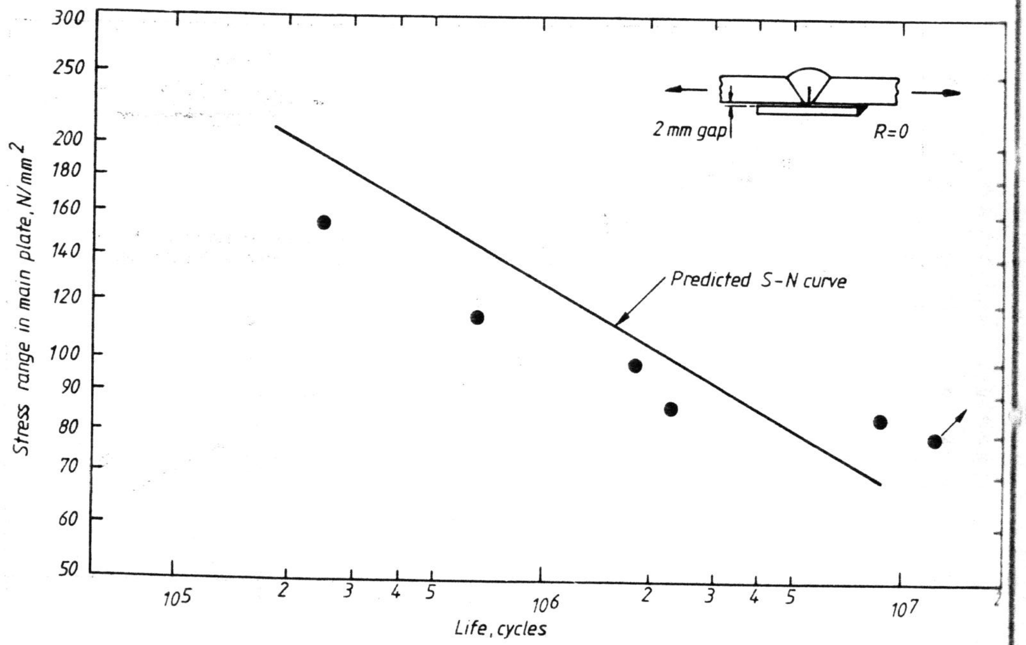

Fig.6. Fatigue test results for Type A Series 3 specimens.

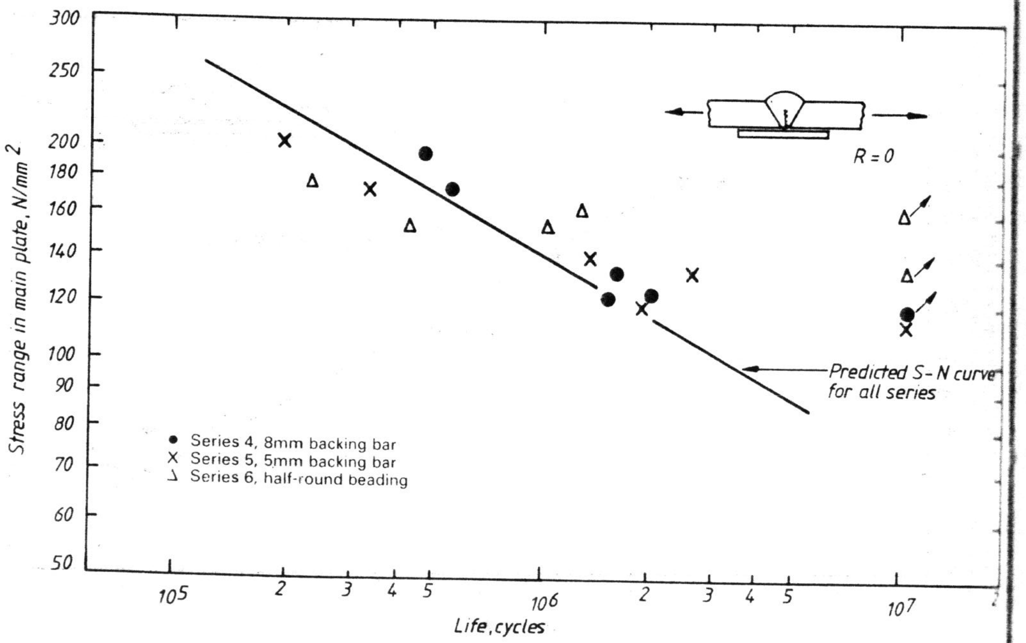

Fig.7. Fatigue test results for Type B specimens.

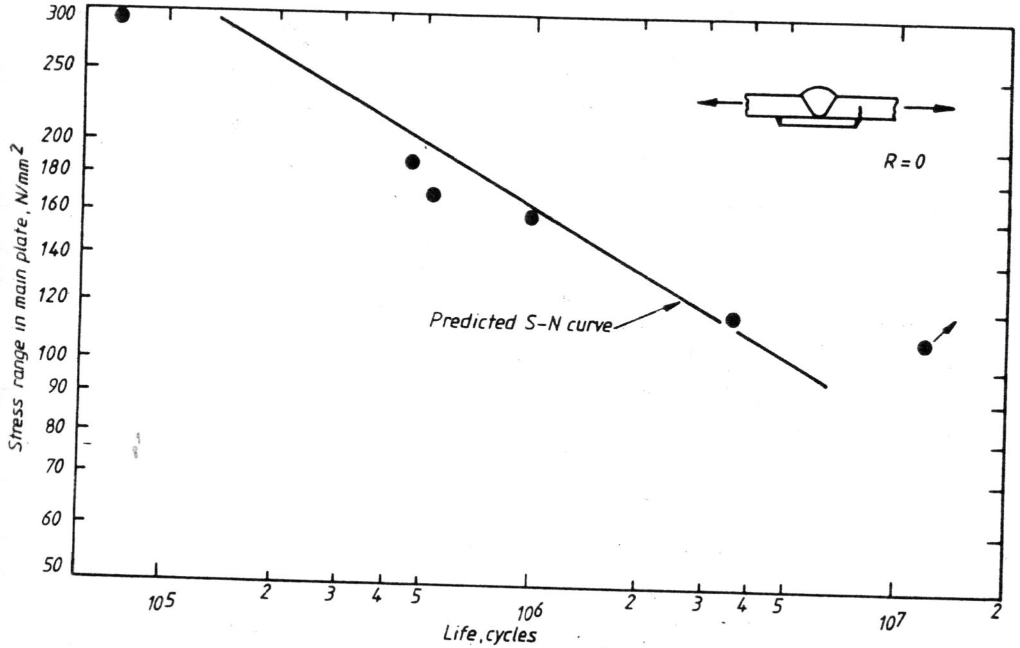

Fig.8. Fatigue test results for Type C (Series 7) specimens.

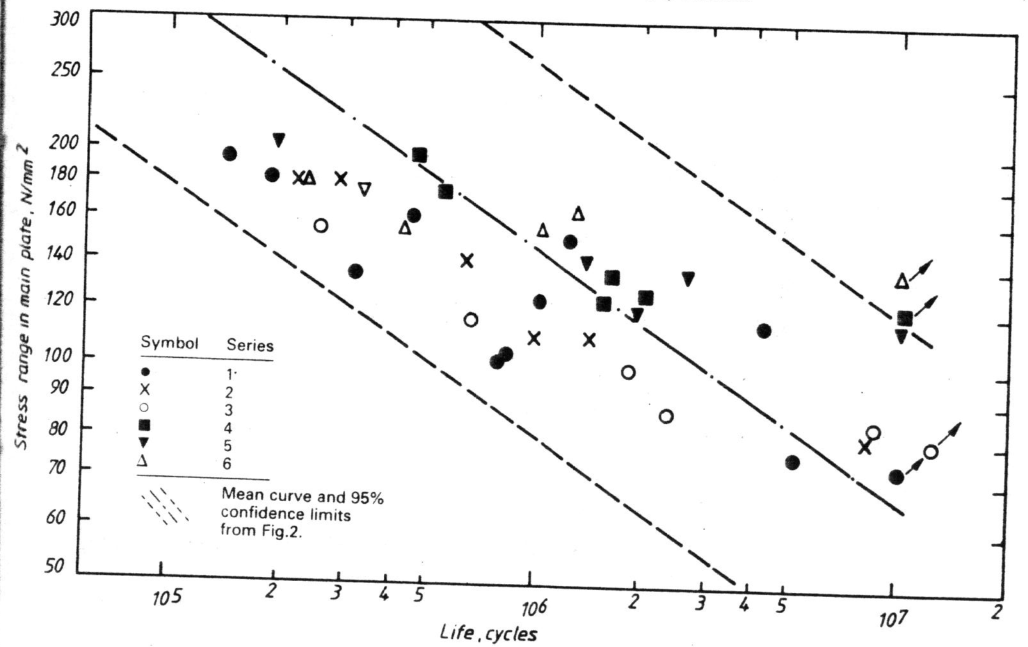

Fig.9. Comparison of present results for failure in the butt weld and published data.

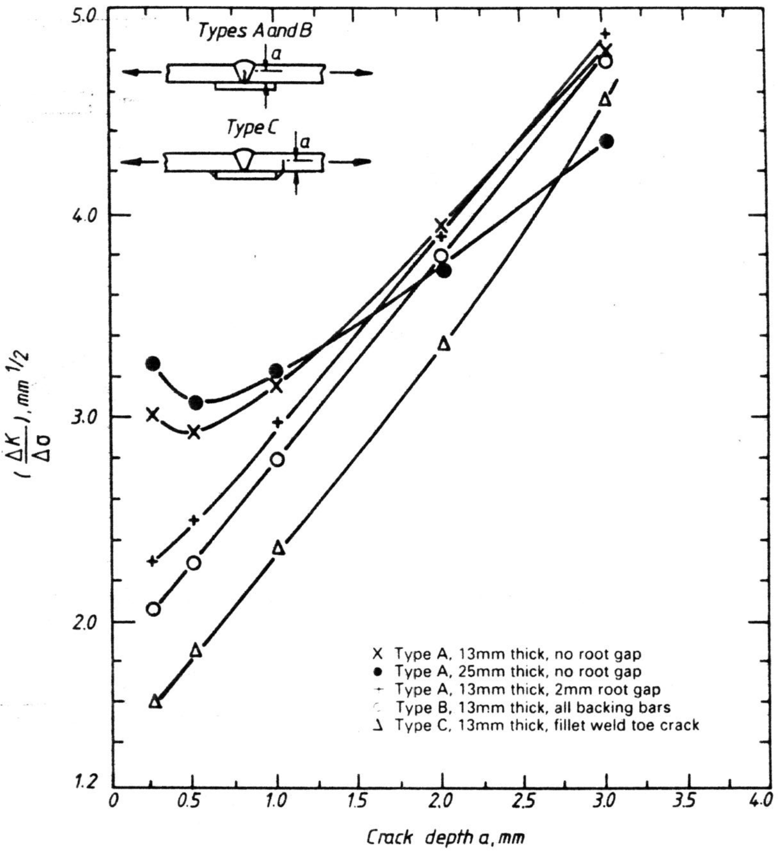

Fig. 10. Stress intensity factors obtained from finite element analysis.

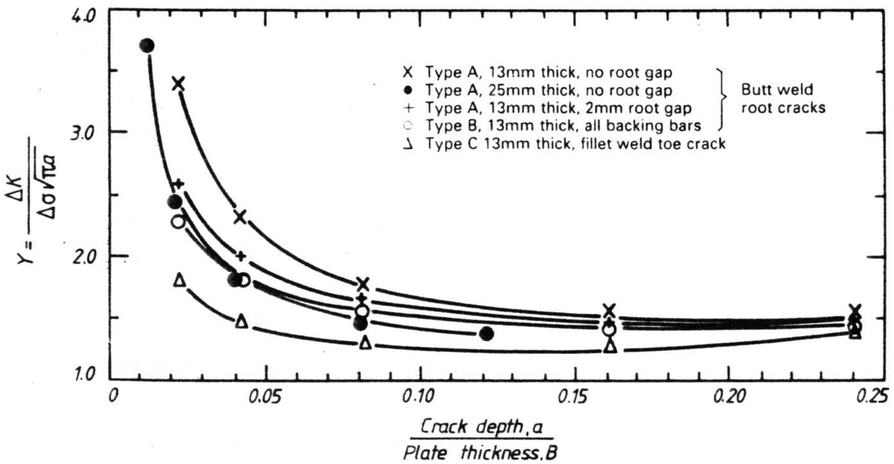

Fig. 11. Stress intensity factor correction term Y as a function of crack depth for cracks within the region of influence of the stress concentration

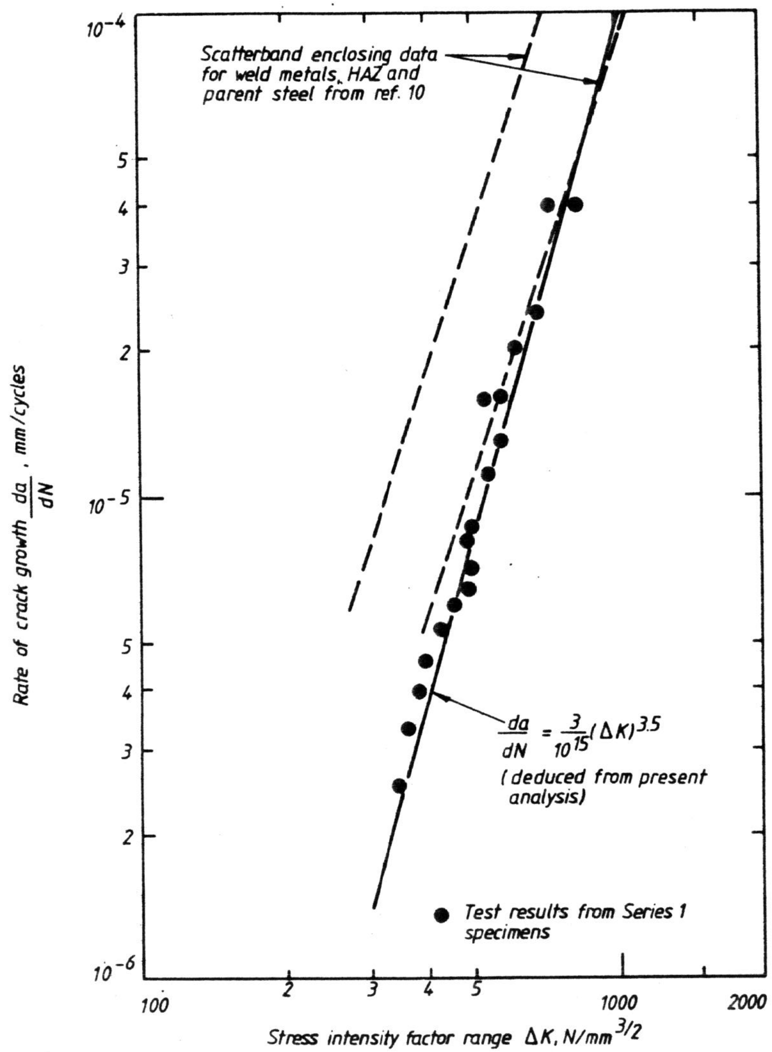

Fig. 12. Fatigue crack propagation results.