Transactions on Engineering Sciences vol 8, © 1995 WIT Press, www.witpress.com, ISSN 1743-3533

Fatigue performance of friction stir butt welds in a 6000 series aluminum alloy

P.J. Haagensen[a], O.T. Midling[b], M. Ranes[c]
[a]*Faculty of Civil Engineering, The Norwegian Institute of Technology, University of Trondheim, Rich. Birkelandsvei 1c, N-7034 Trondheim, Norway*
[b]*Norsk Hydro Aluminum, R&D Centre, Karmøy, Norway*
[c]*SINTEF Production Engineering, Trondheim, Norway*

ABSTRACT

Friction stir welding is a novel solid state joining process for making low cost, energy efficient butt welds in aluminum alloy extrusions. The plate edges are clamped against a backing plate and the material is plastically deformed and stirred by a rotating tool moving along the joint line. The resulting weld bead is flush with the surface and exhibits little distortion. The material in the weld and heat affected zone (HAZ) has a fine-grained microstructure and a high tensile strength compared with welds produced by conventional arc welding methods. The present investigation was undertaken to determine the fatigue properties of friction stir welds in 5 mm thick plates in an AA6082 alloy. Extruded plates in the T4 condition were used in the test program. S-N tests in pulsating tension at R = 0.5 were performed on specimens with the weld transverse to the stress direction. Reference tests were made on the base material. Crack growth data were obtained for material in the weld metal, in the HAZ and base material. S-N tests were also made on conventional MIG butt welds from the same batch material to enable a comparison of the two welding methods. The results indicate that the fatigue strength of transverse friction stir welds is approximately 50 percent higher than the fatigue strength of MIG butt welds. The crack growth rates obtained for the weld material were lower than in the base material, probably due to a more fine grained microstructure in the weld region.

INTRODUCTION

The friction stir welding process has recently been developed as a cost effective alternative to conventional metal inert gas (MIG) and tungsten inert gas (TIG)

Transactions on Engineering Sciences vol 8, © 1995 WIT Press, www.witpress.com, ISSN 1743-3533

welding in aluminum alloys [1]. A major advantage of friction stir welding is that it is a solid state process involving a much lower heat input than that required in conventional arc welding methods. The weld itself and its adjacent narrow heat affected zone both have a very fine-grained microstructure with high mechanical strength.

The high tensile strength of the weld material and the favorable geometry would also indicate that friction stir welds could have high levels of fatigue strength. A testing program was implemented to determine the fatigue properties of transverse butt welds of two alloys in the AA6000 series. The data presented in this paper are results from introductory tests on specimens fabricated from extruded plates in AA6082 material in the T4 temper condition.

THE FRICTION STIR WELDING PROCESS

In friction stir welding the plates to be joined are clamped on a backing plate to prevent movement. A cylindrical shouldered tool with a specially profiled pin is rotated at a high speed, see Fig. 1a. The pin is slowly brought into contact with the joint line, and the material is heated by friction and plasticised in an annular volume around the pin. As the pin is lowered into the plates, soft material is extruded at the surface. Upon further lowering of the pin and movement along the joint line the shoulder face contacts the plate surface and the plasticised material is compressed against the face of the shoulder. The soft material is mashed by the leading face of the pin profile and transported to the trailing face of the pin where it consolidates and cools to form a solid-phase weld. The generation of a friction stir weld has many similarities with extrusion seam welds that form when material is joined in the weld chamber of an extrusion die [2]. The material flow, however, is somewhat different due to the more extensive mechanical mixing of the material from the two plates in the friction stir process. The properties of the weld are closely related to the tool technology. The tool bit shape and material determines the heating, plastic flow and forging pattern. Development of the friction stir welding process has up to now been concentrated mainly on butt and lap joints, however, introductory tests have shown that friction stir welding is suitable for a wide range of joint configurations [4], as shown in Fig. 2.

EXPERIMENTAL PROGRAM

Material

The specimens were fabricated from AA6082 alloy plate material, in the T4 (as-extruded) condition. The plate thickness was 5 mm. The mechanical properties are listed in Table 1.

Table 1. *Mechanical properties of the AA6082 alloy in T4 temper.*

Material	**$R_{p0.2}$ (MPa)**	**R_m (MPa)**	**A_5 (%)**
Base material	153	258	26

Welding equipment and tooling

Friction stir welding was performed by means of a 7.5 kW Köpings milling machine. The tooling used is shown in Fig. 1b). The rotating tool consists of a 15 mm diameter cylindrical part made of high strength die steel, H13. The high strength steel pin had a diameter of 6 mm. The pin had two concentric fins projecting from the circumference as indicated in Fig. 1b).

Specimen geometry and fabrication

The geometry and dimensions of the specimens used in S-N tests and crack growth testing are shown in Fig. 3a and 3b, respectively. The weld was transverse to the stress axis in the S-N specimen. The crack growth specimen conforms to ASTM specifications [3] for the compact tension (CT) specimen.

MIG welding was performed on a permanent backing strip in the downhand position under the conditions listed in Table 2. The test specimens were cut by cold sawing from the welded plates.

Table 2. *Welding conditions for butt welds produced by friction stir welding or MIG welding.*

Welding process	**Process parameters**
Friction stir welding	Tool rotational speed: 1150 rev./min. Welding speed: 500 mm/min
Manual inert gas (MIG) welding on permanent backing	Shielding gas: Argon Consumable: AA5183 Current: 243 A Voltage: 21.3 V Welding speed: 560 mm/min Heat input: 0.55 kJ/mm

S-N tests

The specimens were tested under axial loading in a servo-hydraulic fatigue testing machine equipped with an actuator of 10 kN load capacity. All tests were run in load control. The correlation between axial stress in the specimen and actuator load signal was verified by strain gage measurements on one specimen. Testing was performed at a room temperature of approximately 20°C. Test frequency was 10 Hz. The tests were run at a load ratio of R = 0.5. The applied load ranges were selected to produce fatigue lives in the range 10^5 to 10^6 cycles. Failure was defined to have taken place when the specimen had separated into two parts.

Crack growth tests

The tests were performed in a servo-hydraulic testing machine with a load capacity of 10 kN. The tests were performed at a R-ratio of 0.5 and a frequency of 40 to 45 Hz. The crack length was measured optically by means of a travelling microscope with magnifications of 6.4X, 16X and 40X. The accuracy of the crack length measurements was approximately 0.1 mm.

RESULTS

Surface condition of welded specimens

In a recent investigation [4] involving variation of important process parameters, it was found that the quality of the top surface is critically dependent on the tool down-load shoulder force, which in turn is related to the rotational speed and welding speed. While the top surface of the weld in the present tests has a considerably higher roughness than the unwelded plate surface due to the tool marks, see Fig. 4, these irregularities apparently had no influence on crack initiation, as discussed later.

The MIG welded specimens exhibited an unfavorable local geometry at the transition between the backing bar and the plate, as shown in Fig. 5. Visual inspection indicated that the weld angle and transition radius at this location varied considerably along the length of the weld.

Static strength of welds

Results of mechanical strength tests on welded joints are given in the table below.

Table 3. *Static strength properties of welded joints and base material*

Material	**$R_{p0.2}$ (MPa)**	**R_m (MPa)**	**A_5 (%)**
Friction stir weld[1)]	144	239	17
MIG weld[2)]	129	165	3
Base material (from Table 1)	153	258	26

[1)] Fracture initiation in weld material
[2)] Fracture initiation at backing bar

It is noted that the loss in fracture strength R_m for the friction stir weld is only about 7 percent, while the loss of strength for the MIG weld is 36 percent. Also the reduction in fracture ductility is much lower for the friction stir weld compared with the MIG weld.

S-N tests

Fracture surfaces. All fatigue cracks in the S-N tests on friction stir welds had initiated in defects located in the lower part of the weld. These defects can be described as lack of fusion defects or pores and are evident in transverse macrosections of the weld, an example is shown in Fig. 6. The cracks had apparently reached the root surface first and then grown toward the top surface where the final fracture had taken place, as evidenced by the presence of shear lips, see Fig 7.

In the MIG welded specimens the fatigue cracks had initiated at the root surface, at the sharp transition at the backing bar.

S-N curves. Linear regression analysis was used to calculate best fit mean life S-N curves for the failed specimens. The test results for each test series are plotted in an S-N diagram with logarithmic axes in Fig. 8. The stress range plotted in the diagrams is the nominal stress based on the output from the actuator load cell. The S-N data obtained from the regression analysis are summarized in Table 4.

In some codes the lower 95% confidence limit, corresponding to a probability of survival of 2.5 %, is used as a design curve. Therefore the lower 95% confidence limit was calculated for the three sets of S-N data obtained in the tests to enable a comparison with design codes. The results are plotted in Fig. 9, together with the S-N curves for plain (unwelded) material and for transverse butt welds from BS 8118 [7]. Due to the large scatter evident from the MIG weld data the calculated "design curve" for these welds is considerably lower

Transactions on Engineering Sciences vol 8, © 1995 WIT Press, www.witpress.com, ISSN 1743-3533

than the BS 8118 curve for transverse butt welds. The curve for the friction stir welds, however, is higher than the BS 8118 curve.

Table 4. *Details of mean life S-N curves obtained from regression analysis of test results.*

Test series	**S-N curve: $N(\Delta S)^m = C$**		**Standard deviation of log N**	**Fatigue strength at 2×10^6 cycles**	
	m	**C (m/cycle, MPa√m)**		**Stress range $\Delta S_{2\ mill}$**	**Percent of base material fatigue strength**
Base material	12.7	2.257×10^{32}	0.07	112	100
Friction stir weld	5.35	4.164×10^{15}	0.05	56	50
MIG weld	7.10	2.234×10^{17}	0.32	36	32

Crack Growth Data

Crack growth data was obtained at four locations relative to the weld, as indicated in Fig. 10, location III corresponding to the middle of the weld, and location IV to the base material outside the weld. Assuming a linear relationship between crack growth rate da/dN and stress intensity range, the constants C and m in Paris' equation

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

were obtained from regression analysis. The mean line crack growth curves obtained from the regression analysis are plotted in Fig. 10. Also shown in Fig. 10 are the values of C and m obtained for the material at the different locations.

DISCUSSION

S-N tests.

In each of the three test series from 4 to 10 specimens were tested. While more specimens would have provided a better statistical basis for the observed trends,

Transactions on Engineering Sciences vol 8, © 1995 WIT Press, www.witpress.com, ISSN 1743-3533

the tests were carried at stress levels spaced as far apart as possible within the endurance range aimed for to obtain maximum confidence in the estimates of the two parameters that define the S-N curve. Hence the mean S-N curves are considered to indicate valid trends within this endurance rage and therefore allow comparison to be made with existing design rules and other experimental data. However, due to the low levels of residual stresses that generally are present in small scale specimens the mean life curves obtained from such specimens have a lower slope than large scale specimens containing high residual stresses. A comparison with design curves pertaining to full scale structures therefore involves considerable uncertainties. With this limitation in mind a comparison with the BS 8118 curves still can be useful. It should also be noted that the fatigue tests were performed at an R-ratio of 0.5 which would at least partly compensate for the lack of high residual stresses in the transverse direction.

A comparison of the mean life curves in Fig. 8 indicates that the fatigue performance of friction stir welds is considerable better than that of MIG welds. Both curves, however, are lower than the S-N curve for the base material. For the MIG welds the low fatigue strength can readily be explained by the severe notch present at the lower surface of the weld, see Fig. 5. The friction stir weld, however, aside from the surface roughness associated with the tool marks has no macroscopic stress raisers at the surface. Additionally, the crack growth properties of the material in the weld and the heat affected zone are as good as or better than in the base material. The relatively low fatigue strength of the friction stir welds compared with the unwelded plate material can therefore be attributed mainly to the interior defects shown in Fig. 6.

In Fig. 9 the three "design" S-N curves (the lower 95% confidence limits) from the tests are plotted with the corresponding BS 8118 curves, i.e. the curves for base material (Class 60) and transverse butt welds welded from one side on permanent backing (Class 24). The base material curve is considerably higher than the corresponding BS 8118 curve. Also the friction stir curve is much higher than the Class 24 curve, especially in the long life region. The MIG weld is also somewhat higher than the Class 24 curve in the long life region, but the curves intersect at longer lives.

<u>Crack growth tests</u>

Data from Refs 5 and 6 shown in Fig.10 indicate that the crack growth rates of the material in the weld and in the HAZ are lower than in the base material; this is probably due to the smaller grain size in these regions.

CONCLUSIONS

From an investigation of the fatigue properties of friction stir and MIG welds in 5 mm plates in AA6082-T4 material the following main conclusions are drawn.

1. The fatigue strength of friction stir butt welds was 50 % of the base material fatigue strength in the low stress, long life region of the S-N diagram (at 2×10^6 cycles).

2. Fatigue crack initiation was always from interior lack of fusion defects in the friction stir welds.

3. MIG butt welds had a fatigue strength of 32 % of the base material fatigue strength at 2×10^6 cycles.

4. The scatter in S-N data for the friction stir welds was very low compared with the scatter for MIG weld, probably due to considerable variations in local weld geometry at the backing of the MIG welds.

5. The crack growth rates obtained for the HAZ material were lower than in the base material, probably due to a more fine-grained microstructure in the HAZ weld region.

ACKNOWLEDGEMENTS

The authors are grateful to Hydro Aluminum for the permission to publish this paper. The support from Hydro Aluminum R & D Centre who supplied the welded plate material is gratefully acknowledged.

REFERENCES

1. Thomas, W.M et al.: "Friction Stir Butt Welding." International Patent Application No. PtCT/GB92702203 and GB Patent Application No. 9125978.8, 6 Dec. 1991.

2. Midling, O.T.: "Material Flow Behaviour and Structural Integrity of Friction Stir Butt Weldments", Proc. 4th Int. Conf. on Aluminum Alloys, Atlanta, GA, USA, 11th - 16th September 1994.

3. E 647-83 'Standard Test Method for Measurement of Crack Growth Rates', Am. Soc. for Testing of Mat. 1990 Annual Book of ASTM, Volume 3.01

Transactions on Engineering Sciences vol 8, © 1995 WIT Press, www.witpress.com, ISSN 1743-3533

4. Midling, O. T. et al.:"Joining of Aluminum Constructions by friction Stir Welding", Proc. Int. Symp. on Advanced Transportation Applications Dedicated Conf. on Alternative Materials for the Transportation Industry, ISATA27, Achen, Germany 3rdNovember 1994.

5. Michalsen, E.: "Fatigue of Welded Connections in Aluminum Bridges", siv.ing. thesis, December 1994.

6. Dirdal, H.: "Aluminum in Bridge Constructions", Master Thesis, Delft University of Technology, February 1995.

7. British Standards Institution: " BS 8118. Structural use of aluminum. Part 1. Code of practice for design." BSI 1991

Transactions on Engineering Sciences vol 8, © 1995 WIT Press, www.witpress.com, ISSN 1743-3533

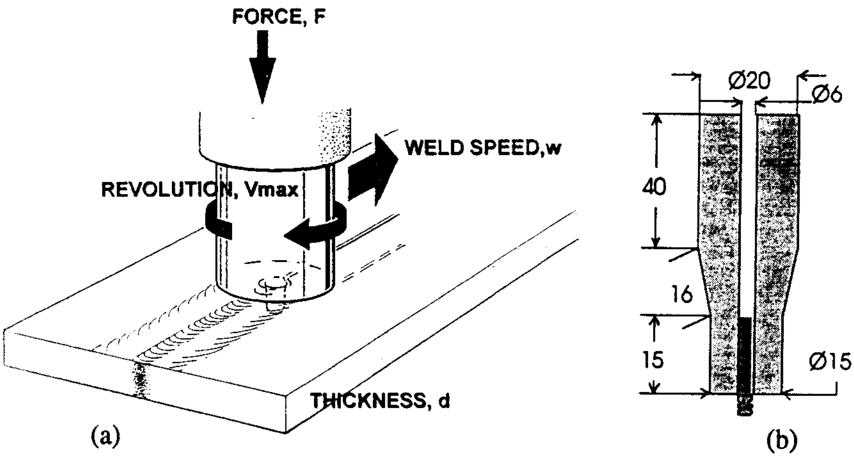


Fig. 1 Friction stir welding [1]; a) welding method, b) welding tool

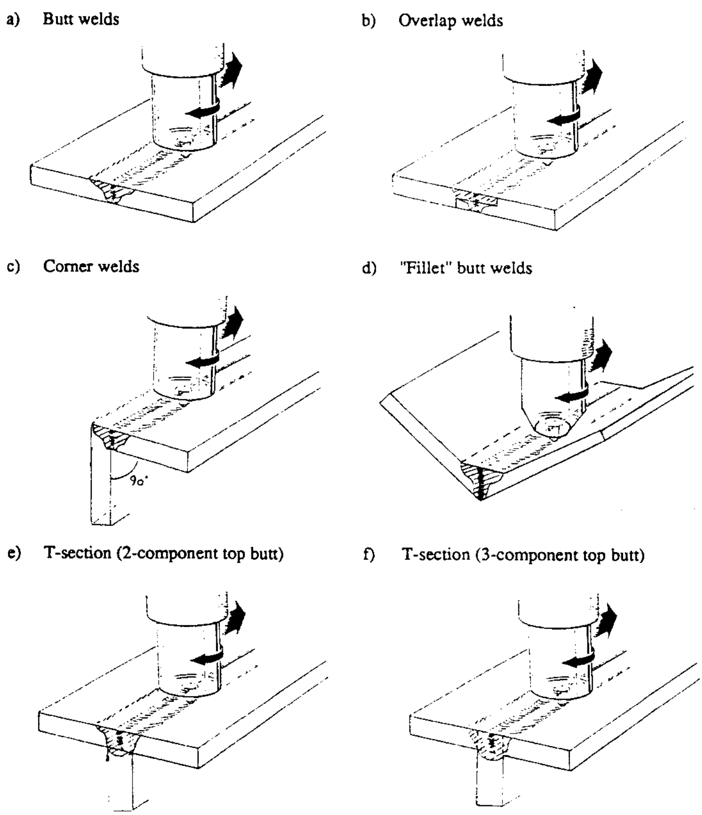


Fig. 2 Joint geometries suited to friction stir welding [4].

Transactions on Engineering Sciences vol 8, © 1995 WIT Press, www.witpress.com, ISSN 1743-3533

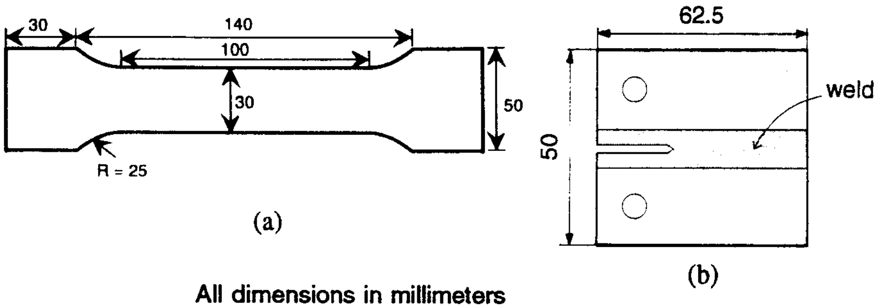


Fig. 3 Geometry of fatigue test specimens; a) S-N test specimen; b) ASTM crack growth specimen.

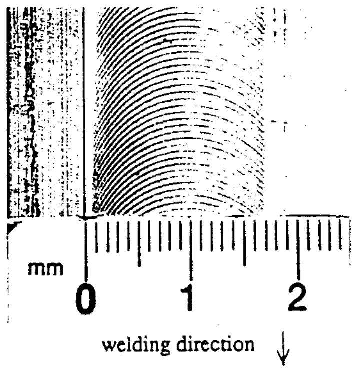


Fig. 4 Surface appearance of friction stir weld

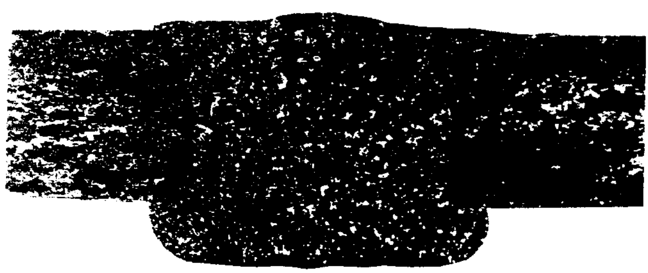


Fig. 5 Geometry of MIG weld

Transactions on Engineering Sciences vol 8, © 1995 WIT Press, www.witpress.com, ISSN 1743-3533

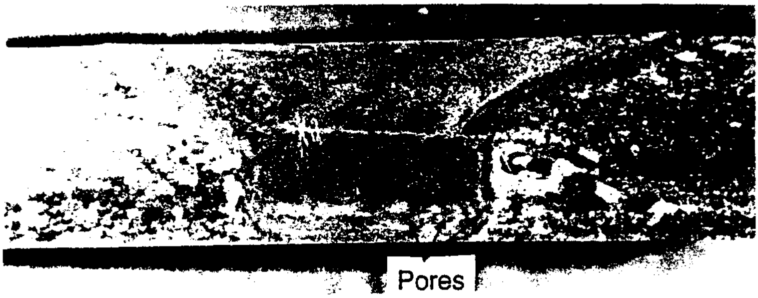


Fig. 6 Macrograph of friction stir weld, showing grain structure and weld defects.

Fig. 7 Fracture surface of friction stir weld fatigue test specimen

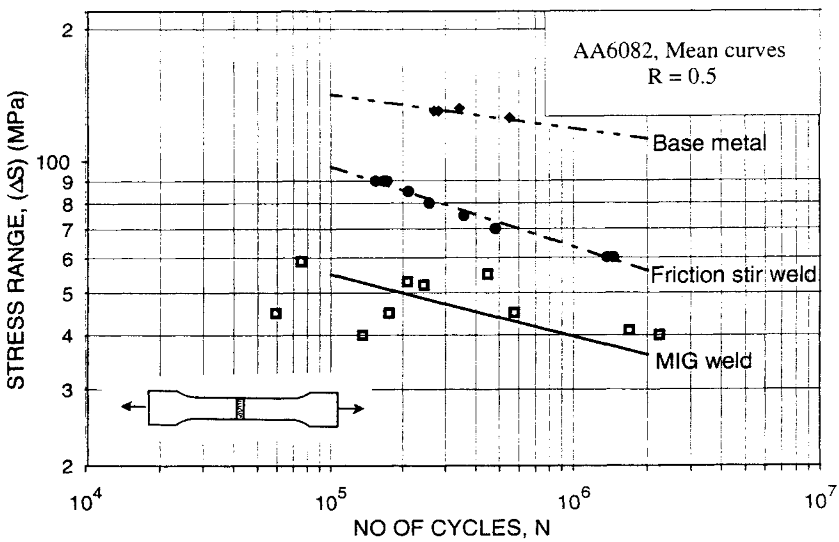


Fig. 8 Test data and mean life S-N curves from regression analysis.

Transactions on Engineering Sciences vol 8, © 1995 WIT Press, www.witpress.com, ISSN 1743-3533

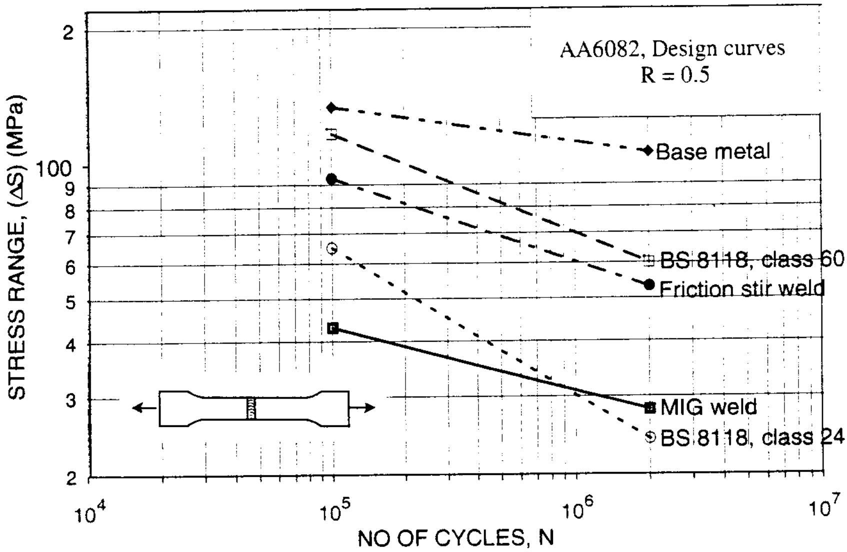
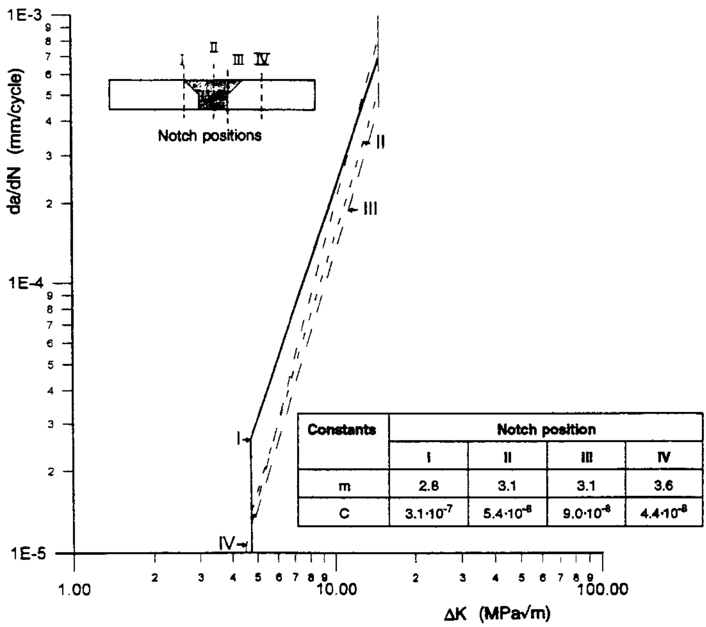


Fig. 9 Design curves based on lower 95 % confidence limit computed from test data compared with BS 8118 [7] design curves.



Constants	Notch position			
	I	II	III	IV
m	2.8	3.1	3.1	3.6
C	$3.1\cdot10^{-7}$	$5.4\cdot10^{-8}$	$9.0\cdot10^{-8}$	$4.4\cdot10^{-8}$

Fig. 10 Crack growth curve in various regions of the weld and in base material, from Refs. 5 and 6.