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Technical Report 85066

July 1985

FATIGUE CRACK PROPAGATION AND FRACTURE TOUGHNESS OF PLASMA ARC WELDED Ti-6Al-4V ALLOY

by

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UNLIMITED

87 12 29 024

UDC 669.295.5.71.292 : 621.791.755 : 539.42 : 620.172.24 :
539.219.2 : 539.431 : 539.211

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SUMMARY

Tensile, fracture toughness and fatigue crack propagation (FCP) data have been determined for a plasma arc weld (PAW) in 4mm thick Ti-6Al-4V alloy sheet. In addition, FCP data is reported for a weld in 9.6mm thick Ti-6Al-4V alloy produced by a PAW root weld and TIG filler runs. In all of the test pieces the stressing direction was normal to the welding direction. Fractures of across-weld test pieces occurred in parent metal, the tensile strength of welded sheet was comparable with that of unwelded parent sheet. The fracture toughness of the welds was also lower than that of the parent metal due to the hard martensitic microstructure produced in the fusion zone as a result of the high post-weld cooling rates. FCP rates, for a given ΔK, were slower in all the welded test pieces compared with parent material by factors of 5-15 for the 4mm thick sheet, and 3-7 for the 9.6mm thick material.

Departmental Reference: Materials/Structures 136

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1 INTRODUCTION

This Report describes the results of an evaluation of a 4mm thick plasma arc welded Ti-6Al-4V alloy sheet supplied by Westland Helicopters Limited (WHL). Tensile, fracture toughness and fatigue crack propagation (FCP) data were obtained for the sheet, which was from the same batch as that used in a larger concurrent evaluation of laser beam welded sheet[1-3]. In addition, FCP data is reported for parent metal and welded 9.6mm thick sheet (plasma arc + TIG filler). These tests at RAE formed part of the support for the welding programme at WHL[4].

2 EXPERIMENTAL TECHNIQUES

2.1 Material

The 4mm thick Ti-6Al-4V alloy sheet was supplied to WHL by the American Metals Service Export Corporation, to MIL-T-9046 type 3, composition C. Two half panels ~150 × 450 mm were degreased in MEK (Methylethylketone) prior to being butt welded by WHL in a single pass using the autogeneous pulsed plasma arc process (see Table 1 for details of welding parameters) to give a panel ~300 × 450 mm ('4th trial' sheet, WHL reference). Test results for parent metal are taken from the laser welded sheet programme[1-3]. Welding parameter details for the 9.6mm thick material[4] are included in Table 1.

No microporosity was detected by radiography and although the weld was undercut along its length, a macrosection through the weld (Fig 1a) showed that the depth of undercutting was very small. Large grains were visible at the centre of the fusion zone with much smaller grains in the heat affected zone (HAZ). The width of the fusion zone + HAZ was 13.0 mm at the top surface and 11.8 mm at the bottom surface of the weld. The microstructure of the fusion zone consisted of martensitic α within the former β grains (Fig 1b). The large fusion and heat affected zones were caused by the slow (0.08 m/min) welding speed.

2.2 Mechanical tests

Tensile, fracture toughness (K_c) and FCP tests were carried out in laboratory air at room temperature on test pieces which were cut from the 4mm thick welded sheet in the LT orientation*. Undercuts were removed by machining equal amounts of metal from both top and bottom surfaces, giving a final thickness of ~3.7 mm. FCP test pieces from 9.6mm plate were machined to ~8 mm. The location of each 4mm thick test piece in the welded sheet is shown in Fig 2. The parent metal test pieces were cut from other sheets as described elsewhere[1].

Tensile tests were carried out on 'B' size metric test pieces according to BS4.A4.

Since the sheet was too thin for valid K_{Ic} values to be determined, K_c tests were carried out according to ASTM E561-81[5] on compact tension test pieces (Fig 3).

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* First letter denotes direction normal to crack plane. Second letter denotes crack growth direction.

Compliance curves had been determined earlier[1,2] using parent metal test pieces to confirm that the crack opening displacement (COD) measurements gave accurate values of crack length.

The FCP tests were carried out using a SEN 3-point bend test piece (Fig 4); side-plates were bolted to both sides at each end of the 4mm thick test piece to prevent twisting. Tests were carried out in a 2 ton Amsler Vibraphore machine fitted with a solid state Howden HFP-81 controller, with the stress ratio $R = 0.1$. The crack length, 'a', was measured in all but one of the tests using a dc electric potential method[1,6] and was checked optically with a travelling microscope. Test piece No.PLMLE was tested using a recently developed automatic technique[7], in which a microcomputer is used to continuously monitor two dc potentials, and from their ratio, determine instantaneous values of crack length, growth rate and stress intensity range. Details of the 4mm thick test pieces cut from the welded sheet, together with other test pieces supplied by WHL and cut from separate sheets are given in Table 2.

3 RESULTS

3.1 Tensile tests

The results of the tensile tests are shown in Table 3. The across-weld test pieces fractured in the parent metal away from the weld at stresses slightly lower (by 7% (0.1% PS), 4% (0.2% PS), 1.7% (0.5% PS and TS)) than those for the parent metal; ductility values, especially elongation, were also lower. These strength and ductility values are typical of across-weld test pieces, and are caused by slight annealing of the parent metal, and reduced ductility in the harder fusion zone.

3.2 Fracture toughness

The results of the fracture toughness (K_c) tests are shown in Table 4. The two K_c values obtained for the parent metal, and one for the fusion zone of a welded test piece, did not satisfy the validity criteria. In one of the parent metal test pieces (PMML1) the crack deviated by $\sim 90^\circ$ from the normal crack growth direction (Fig 5a) due to preferred orientation in the sheet[1]. In the welded test pieces crack growth remained in the fusion zones throughout the duration of the tests (Fig 5b). The valid K_c value of 108.1 $MPa\sqrt{m}$ obtained for fusion zone material (PLML1, Table 4) is much higher than values obtained for faster cooled laser beam fusion zones[1,2]. Banas[8] obtained values of 63.3, 66.2 and 73.4 $MPa\sqrt{m}$ in plasma welded 6.4mm thick Ti-6Al-4V alloy*. The higher value obtained in this work was probably due to the slow welding speed used, which resulted in a coarse grain size and tough fusion zone.

3.3 Fatigue crack propagation

Fatigue crack growth curves for the 4mm thick parent metal (Fig 6a) and plasma welded sheet test pieces (Fig 6b) showed good agreement between test piece pairs (A & B) cut from the same sheets.

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* Fracture toughness values in Ref 8 had incorrect units; corrected values are given here.

Growth rates in test piece PLMLC, cut from a different sheet and supplied by WHL, were faster for a given ΔK, than those for the sheet in Fig 2 (test pieces PLMLA and PLMLB), as shown in Fig 6b. Mean fatigue crack growth rates are plotted in Fig 6c. For a given ΔK growth rates were always significantly slower in plasma welded fusion zones compared to the parent metal, especially at low ΔK values (Table 5); for mean ΔK values of 20 and 25 $MPa\sqrt{m}$ (Fig 6c), crack growths in the fusion zones were slower than in the parent metal by factors of 15.6 and 5.2, respectively.

Fatigue crack growth curves for the 9.6mm thick material are shown in Fig 7. The curve for the parent metal test piece was similar to the corresponding curve for the 4mm thick material (Fig 6c). Fatigue crack growth rates in the fusion zones were slower than in the parent metal by factors of 3.4 and 6.6, at ΔK values of 15 and 20 $MPa\sqrt{m}$, respectively. Growth rates in the fusion zones were the same as those determined for the 4mm thick test piece PLMLC (Fig 6b) and for 4mm thick sheet which had been laser beam welded at 5 kW and 2 m/min[1-3].

4 DISCUSSION

The plasma arc weld examined in this Report is probably not typical of PAW titanium alloy sheet; this is because the welding equipment, a Thermal Arc WC122A Welding Console, was being used at its maximum capacity[4]. This necessitated the use of a slow traverse speed resulting in a relatively wide and slowly cooled weld. A higher capacity machine would have been operated at a faster welding speed, resulting in higher cooling rates and therefore different microstructures and mechanical properties. However, the welds produced were pore-free with minimal undercutting and satisfactory mechanical properties. A faster postweld cooling rate would probably result in lower fracture toughness, and a stress relief heat treatment for 4.5 h @ 625°C could reduce the FCP resistance to that of the parent material, based upon preliminary results obtained on laser beam welded sheet[9].

If welded sheet was to be used without removal of undercuts then S/N data would be required. The fatigue strength (S/N) of the PAW sheet used in the current work was reported to be approximately half that of the parent metal sheet[4]; the cracks initiated at notches present in the top surface 'ripple' at the edge of the fusion zone. In work carried out on laser beam welds it was shown that the presence of undercuts (up to 0.2 mm deep) significantly reduced the fatigue strength of the sheet[1-3].

5 CONCLUSIONS

(1) Across-weld test piece from a 4mm thick Ti-6Al-4V alloy plasma arc welded joint failed in the parent metal and the tensile strength was comparable with that of parent metal; ductility values of welded sheet were lower however by 40% (elongation) and 15% (reduction of area).

(2) Fracture toughness values were difficult to measure accurately; the only valid K_c value obtained was 108.1 $MPa\sqrt{m}$ for 4mm thick plasma welded surface machined sheet.

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(3) Fatigue crack growth rates in the fusion zones of welded 4mm and 9.6mm thick material were slower, for a given stress intensity >20 $MPa\sqrt{m}$, by factors in the range 3.4 to 6.6 compared to the parent metal; the factor was >15 at stress intensities <20 $MPa\sqrt{m}$ in the 4mm thick welded sheet.

Table 1

PLASMA ARC WELDING PARAMETERS[4]

Sheet thickness	mm	4	9.6		
Pass number		1	1	2	3
Weld type		Pulsed plasma		TIG filler	
Weld current	A	100	110	205	205
Top pulse time	s	0.4	0.6	-	-
Background current	A	10	10	-	-
Lower pulse time	s	0.2	0.2	-	-
Slope up	A/s	20	20	50	50
Sequence terminate	A/s	10	10	20	20
	A	8	8	10	10
Carriage speed	m/min	0.08	0.04	0.13	0.13
Shielding gas flow rate	ℓ/min	10	10	10	10
Plasma flow rate	ℓ/min	1.5	1.5	-	-
Trailing shield flow rate	ℓ/min	14	14	14	14
Backing gas flow rate	ℓ/min	14	14	14	14
Arc voltage	V	-	-	11	11
Wire feed	m/min	-	-	1.95	1.95
Up slope	s	-	-	2.0	2.0
Down slope	s	-	-	0.5	0.5
Oscillating speed	%	-	-	80	70
Traverse distance	mm	-	-	1	2

Table 2

DATA FOR FATIGUE CRACK PROPAGATION TEST PIECES
(Surface machined, LT orientation, R = 0.1)

Parent metal or weld	Mark†	Thickness, mm	
		Initial	Machined
PM	PMMLA●	4	3.74
	PMMLB		3.73
Weld 0.08 m/min	PLMLA		3.50
	PLMLB		3.58
	PLMLC⊕		3.31
PM	PMMLI●	9.6	8.37
Weld*	PLMLE●▲		7.72

* PAW root · TIG fillers

† PM = Parent metal
M = Machined surface
L or T = direction normal to crack plane
PL = Plasma welded

● Test pieces supplied separately by Westland Helicopters Limited

▲ Tested using automatic computer controlled technique[7]

Table 3

TENSILE TEST RESULTS OF PLASMA ARC WELDED 4MM THICK Ti-6Al-4V ALLOY SHEET
(Surface machined, LT orientation)

Parent metal or weld	Mark	Sheet No.	0.1% PS MPa	0.2% PS MPa	0.5% PS MPa	TS MPa	E GPa	Uniform elongation %	Total elongation on 24 mm %	R of A %
PM	PMM/A	A/7520 BD	934	945	956	1007	112	4.8	16	34
	PMM/B		920	937	943	997	112	1.04	16	31.5
	PMM/C	A/7514 TV	932	953	963	1016	112	8.7	16	41.5
	PMM/D		935	952	966	1016	113	9.9	16	33.5
Weld 0.08 m/mm	PLM/A	'4-h trial'	853	900	940	995	112	2.5	[illegible]	29
	PLM/B		882	914	941	1004	107	6.5	9	31

PS = Proof stress
TS = Tensile strength

Table 4

FRACTURE TOUGHNESS DATA FOR PLASMA ARC WELDED 4MM THICK Ti-6Al-4V ALLOY SHEET
(Surface machined, LT orientation)

Parent metal or weld	Mark	Sheet No.	Thickness mm	Final ΔK of fatigue cracking $MPa\sqrt{m}$	Starting* crack length, a_o mm	σ_y ++ MPa	E GPa	K_c $MPa\sqrt{m}$	a^1 mm	$\frac{4}{\pi}\left(\frac{K_c}{\sigma_y}\right)^2$ ** mm	Valid	$r_p = \frac{1}{2\pi}\left(\frac{K_c}{\sigma_y}\right)^2$ +	Comment
PM	PMML1	A/7519 FH	3.63	19.5	13.5	947	112	214.7	20.3	65.0	No	8.2	crack deviated through 90°
	PMML2		3.67	20.8	18.2			137.2	21.6	26.7		3.3	
Weld 0.08 m/min	PLML1	4th trial	3.59	34.9	17.6	907	109.5	108.1	19.6	18.1	Yes	2.3	
	PLML2		3.64	31.3	17.5			122.9	19.8	23.4	No	2.9	

* Starting crack = Notch + Fatigue Crack

** $\frac{4}{\pi}\left(\frac{K}{\sigma_y}\right)^2$ ≤ uncracked ligament to be valid

\+ Plastic zone equation for plane stress

++ σ_y (0.2% PS), mean values from Table 3

Table 5

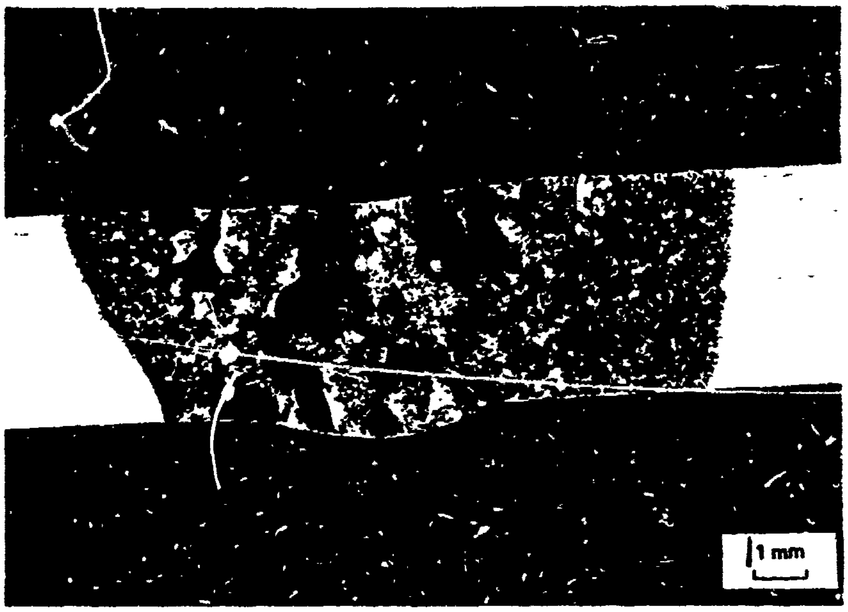
FATIGUE CRACK GROWTH RATES FOR PARENT METAL AND PLASMA WELDED TEST PIECES
(Surface machined, LT orientation, R = 0.1)

Parent metal or weld	Initial sheet thickness mm	Mark	Fatigue crack growth rates, $mm.s^{-1}$, at given ΔK values $MPa\sqrt{m}$					
			10	15	20	25	30	40
PM	4	PMMLA	3.0×10^{-5}	1.0×10^{-4}	2.5×10^{-4}	4.5×10^{-4}		
		PMMLB	2.7×10^{-5}	1.1×10^{-4}	2.7×10^{-4}	4.0×10^{-4}		
		Mean	2.8×10^{-5}	1.1×10^{-4}	2.5×10^{-4}	4.7×10^{-4}		
Plasma arc weld		PLMLA			1.6×10^{-5}	9.1×10^{-5}	1.9×10^{-4}	4.3×10^{-4}
		PLMLB			1.6×10^{-5}	9.1×10^{-5}	1.9×10^{-4}	
		PLMLC			4.8×10^{-5}	1.5×10^{-4}	2.6×10^{-4}	
		Mean (of A and B)		3.0×10^{-6}	1.6×10^{-5}	9.1×10^{-5}	1.9×10^{-4}	4.3×10^{-4}
PM	9.6	PMMLI	1.8×10^{-6}	1.4×10^{-5}	2.9×10^{-4}			
Weld (PAW + TIG filler)		PLMLE		4.1×10^{-6}	4.4×10^{-5}	1.3×10^{-4}	2.5×10^{-4}	4.8×10^{-4}

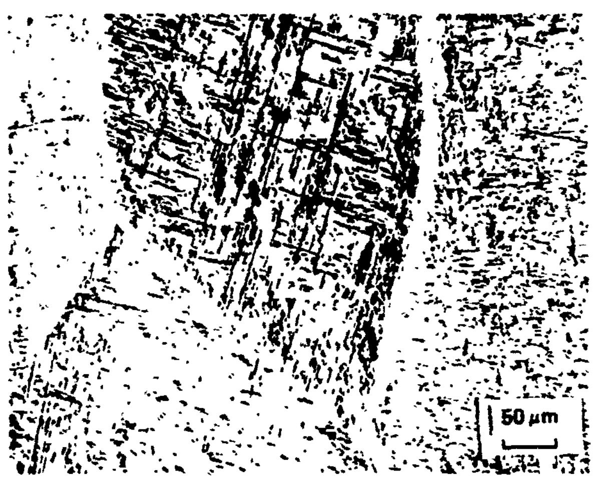
REFERENCES

No.	Author	Title, etc
1	T.S. Baker	Evaluation of laser beam welded 4mm thick Ti-6Al-4V alloy sheet RAE Technical Report 85065 (1985)
2	T.S. Baker P.G. Partridge	Mechanical properties of laser welded 4mm thick Ti-6Al-4V alloy sheet Proc.5th Int.Conf. on Titanium, Munich, 2, 815, 10-14 Sept. 1984
4	T.S. Baker P.G. Partridge	Fatigue properties of 4mm thick laser welded Ti-6Al-4V sheet Proc.2nd Int.Conf. on Fatigue & Fatigue Thresholds, Birmingham, 3, 1763, 3-7 Sept 1984
4	J.E. Penn A. Davies	Evaluation of improved welding techniques Westland Helicopters Ltd. MOD Contract No.A51A/435
5	ASTM	Standard practice for R-curve determination ASTM E561-81
6	D.M. Gilbey S. Pearson	Measurement of the length of a central or edge crack in a sheet of metal by an electrical resistance method RAE Technical Report 66402 (1966)
7	C.M. Ward-Close	A computer-based crack measurement and control system RAE Technical Memorandum MAT 389 (1982)
8	C.M. Banas	Electron beam, laser beam and plasma arc welding studies NASA Contractor Report No.NASA CR-132386 March 1975
9	T.S. Baker	RAE work - to be published

Fig 1



a



b

Fig 1 Section through plasma arc weld in 4mm thick Ti-6Al-4V sheet
(a) macrostructure, (b) microstructure in fusion zone

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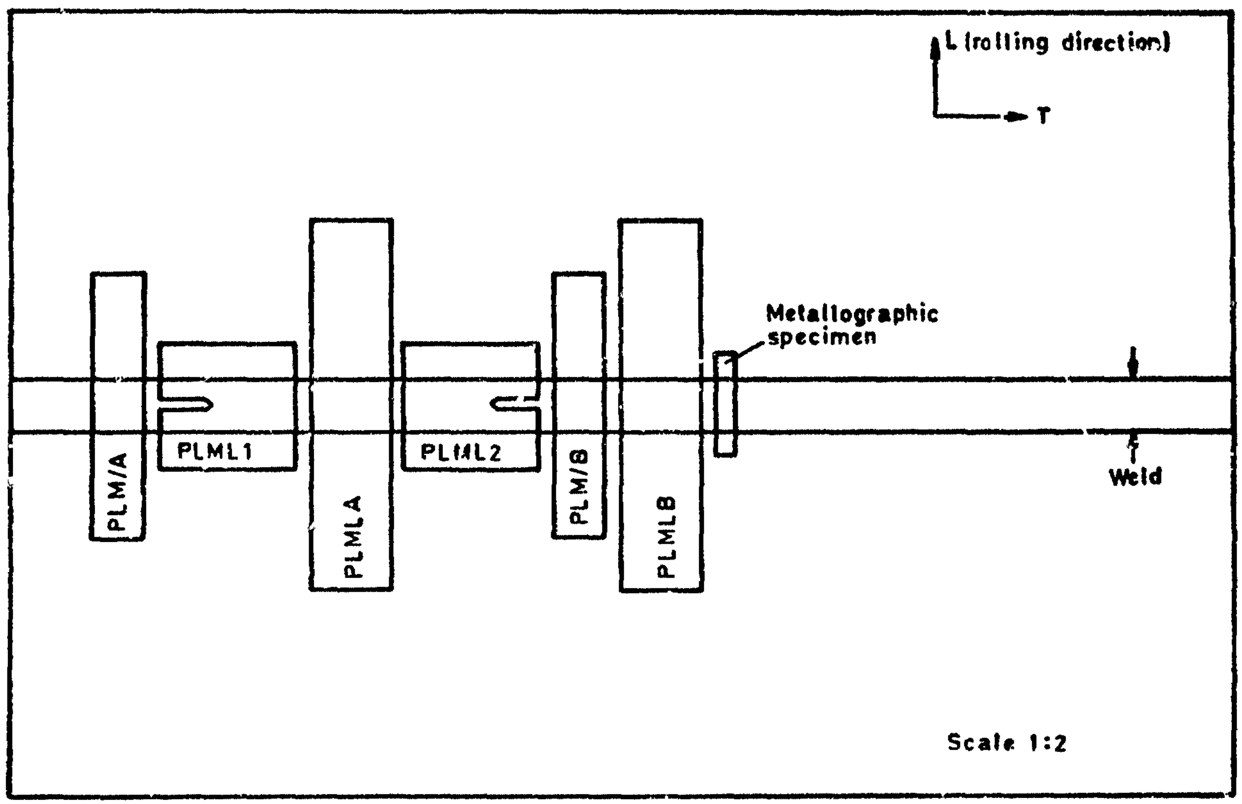
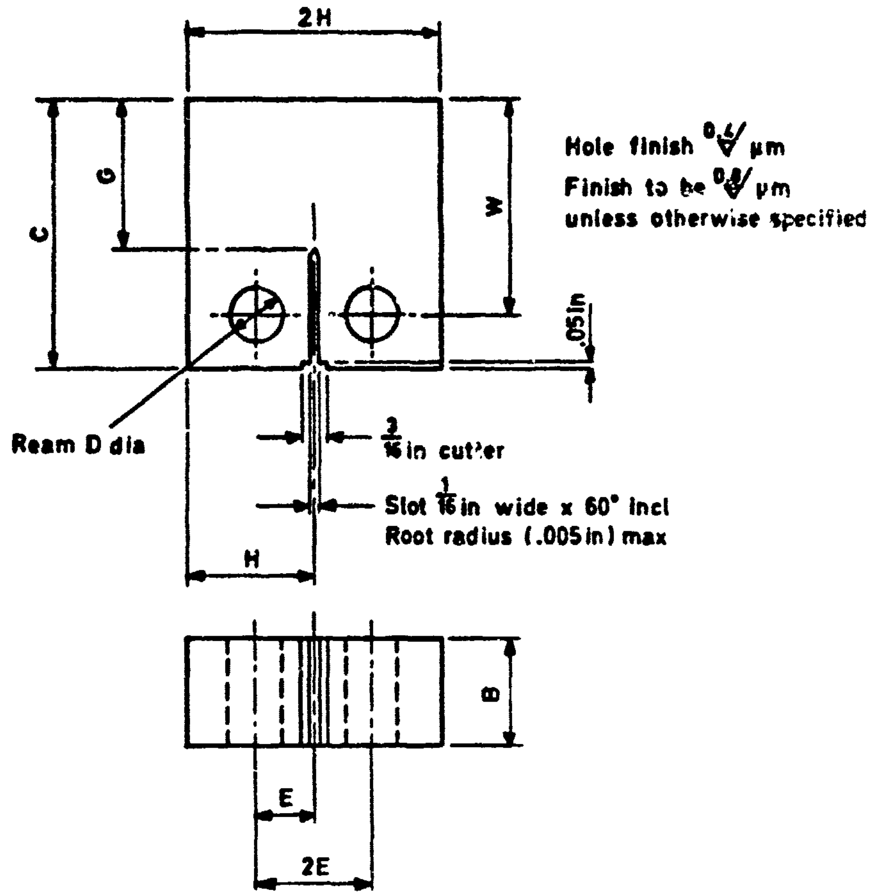


Fig 2 Location of test pieces (tensile, fatigue crack propagation, fracture toughness and metallographic specimen in 4 mm thick Ti-6Al-4V alloy plasma welded sheet



Proportional dimensions	and	Tolerances mm
Net width	W	+0 −0.2
Thickness	B = 0.5W	+0 −0.1
Total width	C = 1.25W	∓0.1
Hole dia	D = Nominal 0.25W (see table)	
Half hole	E = 0.275W	±0.1
centre	H = 0.6W	±0.1
	G = 0.7W	±0.1

Standard test piece sizes

Width mm	Thickness mm	Hole dia reamed
40	20	10 mm

Parallel surfaces to be par⊥ within 0.02mm taper/10mm run
Perpendicular surfaces to be sq within 0.02mm taper/10mm run
The above tolerances must not be cumulative

Fig 3 Fracture toughness test piece

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Fig 4

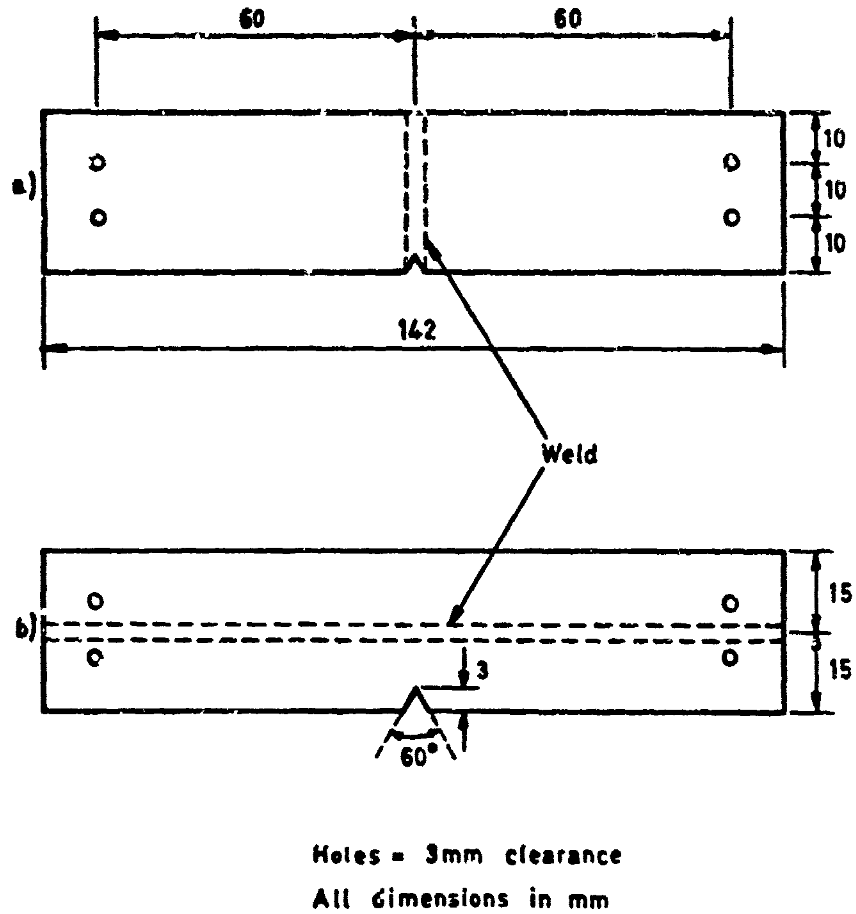

Fig 4 Fatigue crack propagation test pieces
a. LT b. TL orientation

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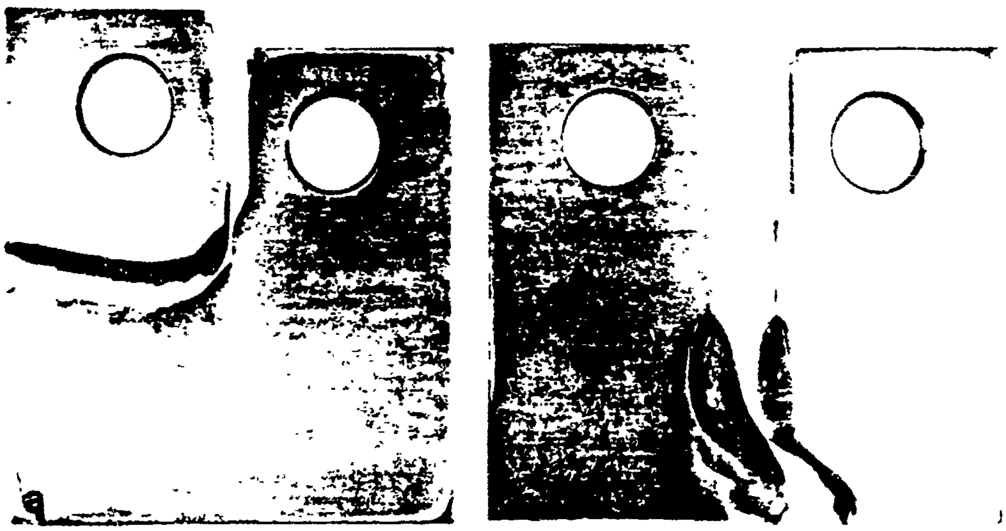
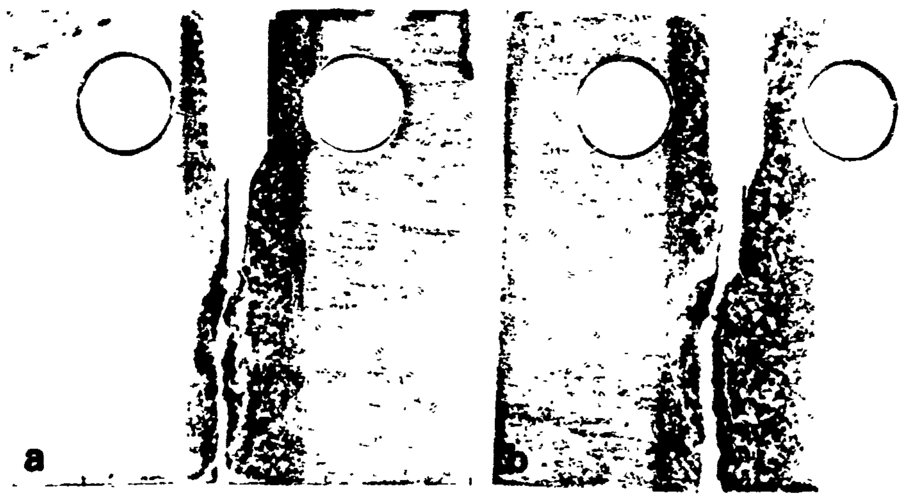


PARENT METAL

5 mm

Fig 5a Fracture toughness (K_c) test piece fractures, (a) PMML1, (b) PMML2



PLASMA WELDED

5 mm

Fig 5b Fracture toughness (K_c) test piece fractures, (a) PLML1, (b) PLML2

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Fig 6a

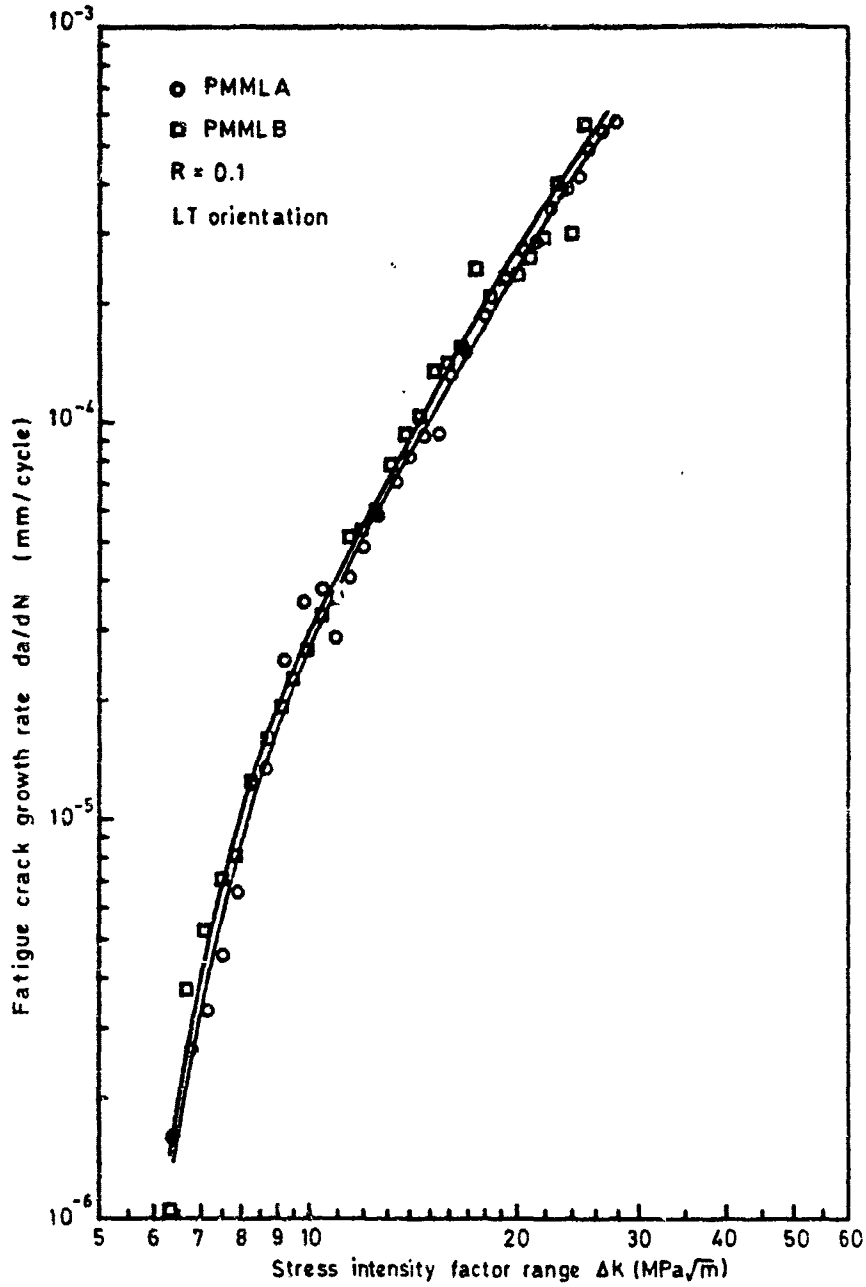

Fig 6a Fatigue crack growth curves for parent metal surface machined 4 mm thick sheet

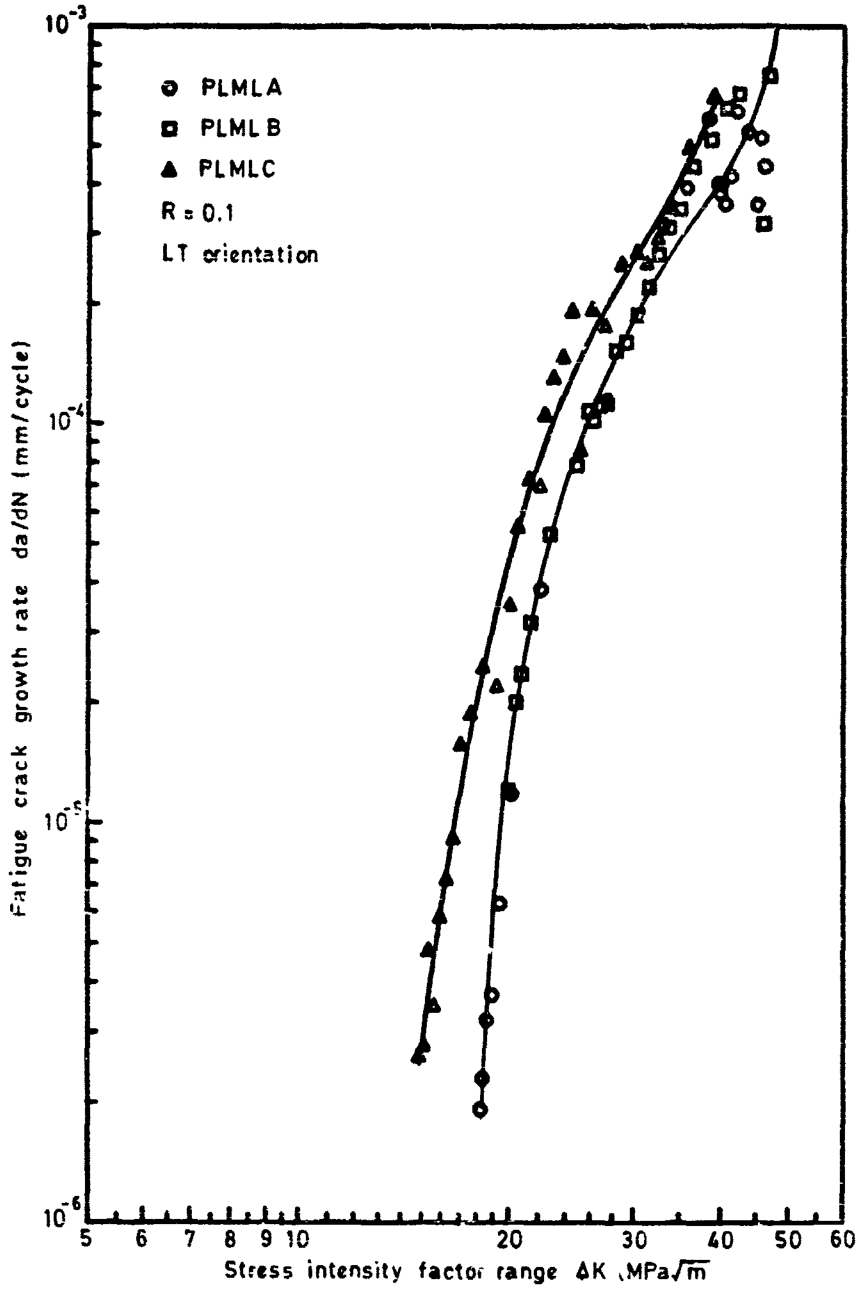

Fig 6b Fatigue crack growth curves for plasma welded and surface machined 4 mm thick sheet

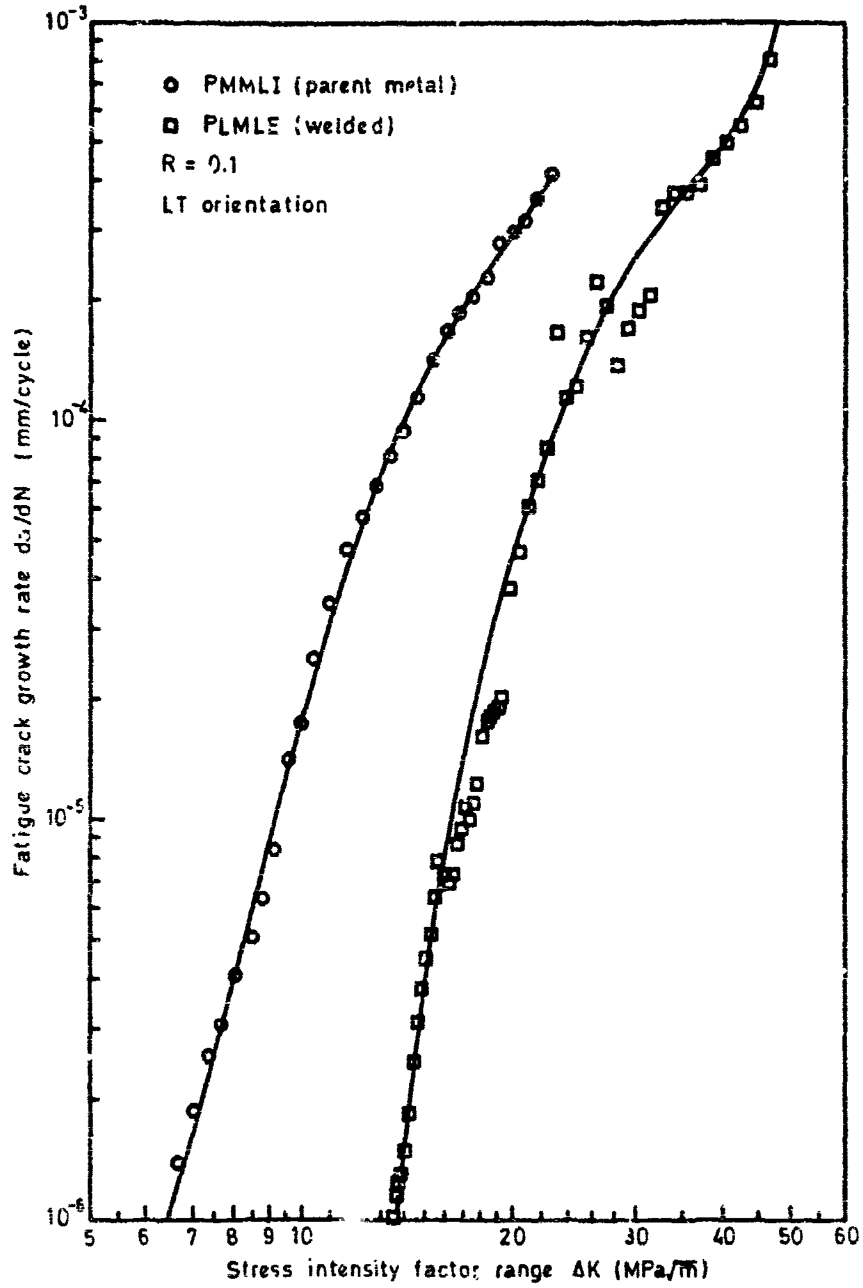

Fig 7 Fatigue crack growth curves for welded (PAW and TIG filler) and parent metal surface machined 9.6 mm thick plate

REPORT DOCUMENTATION PAGE

Overall security classification of this page

UNCLASSIFIED

As far as possible this page should contain only unclassified information. If it is necessary to enter classified information, the box above must be marked to indicate the classification, e.g. Restricted, Confidential or Secret.

1. DRIC Reference (to be added by DRIC)	2. Originator's Reference RAE TR85066	3. Agency Reference N/A	4. Report Security Classification/Marking UNCLASSIFIED

5. DRIC Code for Originator 7673000W	6. Originator (Corporate Author) Name and Location Royal Aircraft Establishment, Farnborough, Hants, UK
5a. Sponsoring Agency's Code N/A	6a. Sponsoring Agency (Contract Authority) Name and Location N/A

7. Title Fatigue crack propagation and fracture toughness of Plasma Arc Welded Ti-6Al-4V Alloy

7a. (For Translations) Title in Foreign Language

7b. (For Conference Papers) Title, Place and Date of Conference

8. Author 1. Surname, Initials Baker, T.S.	9a. Author 2	9b. Authors 3, 4	10. Date July 1985	Pages 21	Refs. 9
11. Contract Number N/A	12. Period N/A	13. Project	14. Other Reference Nos. Mat/Str 136		

15. Distribution statement

(a) Controlled by – AD/XR via DRIC

(b) Special limitations (if any) –

16. Descriptors (Keywords) (Descriptors marked * are selected from TEST)

17. Abstract

Tensile, fracture toughness and fatigue crack propagation (FCP) data have been determined for a plasma arc weld (PAW) in 4mm thick Ti-6Al-4V alloy sheet. In addition, FCP data is reported for a weld in 9.6mm thick Ti-6Al-4V alloy produced by a PAW root weld and TIG filler runs. In all of the test pieces the stressing direction was normal to the welding direction. Fractures of across-weld tensile test pieces occurred in parent metal; the tensile strength of welded sheet was comparable with that of unwelded parent sheet. The fracture toughness of the welds was lower than that of the parent metal due to the hard martensitic microstructure produced in the fusion zone as a result of the high post-weld cooling rates. FCP rates, for a given ΔK, were slower in all the welded test pieces compared with parent material by factors of 5-15 for the 4mm thick sheet, and 3-7 for the 9.6mm thick material.

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