THE FRACTURE TOUGHNESS OF TYPE 316 STEEL AND WELD METAL

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SUMMARY

This paper describes the results of fracture toughness tests on Type 316 steel and Manual Metal Arc (MMA) weld metal over a range of temperatures from 20°C to 550°C, and includes the effects on toughness of specimen size, post weld heat treatment and thermal ageing. The conclusions reached are that Type 316 steel possesses a superior toughness to the weld metal in the as-welded or stress relieved conditions but the toughness of the steel is degraded to a level similar to that of the weld metal following thermal ageing at temperatures over 600°C. Relatively short term thermal ageing in the temperature range 370°C to 450°C does not appear to affect the toughness of either Type 316 steel or weld metal.

1. INTRODUCTION

To provide data for the assessment of flawed structures within the primary circuit of the Commercial Demonstration Fast Reactor (CDFR), fracture toughness tests have been made on the materials of interest - Type 316 stainless steel - and the weld metal of 17Cr-8Ni-2Mo composition expected to be used with it. Because acceptable flaw size calculations can be heavily influenced by the high (up to yield stress) residual stresses possible in as-welded structures, much of the work completed has concentrated on materials in the dimensionally stabilised (2h 650°C) or stress relieved (2h 850°C) conditions. Present indications suggest that, in practice, the spread of plasticity at the tip of the flaw may be sufficient to mechanically relieve the local residual stresses so they are not additive to the applied stresses. Accordingly greater emphasis is now being placed on the measurement of fracture toughness of solution treated wrought plate and as-welded weld metal.

The potentially embrittling effects of prolonged thermal exposure at both sodium pool temperatures (< 400°C) and core outlet temperatures (500/600°C) and of fast neutron irradiation for core peripheral itmes are also under investigation. This paper reports fracture toughness data on wrought Type 316 steel and 17-8-2 Manual Metal Arc (MMA) weld metal from both baseline and thermal ageing test programmes; the effects of fast neutron irradiation on fracture toughness are reported in a separate paper(1).

2. EXPERIMENTAL TECHNIQUES

Although some tests have been made at room temperature using compact specimens, the majority of fracture toughness tests on Type 316 steel and weld metal have been made in air by the interrupted multi-specimen technique(2), using square-section single-edge-notched 3-point bend (SENB 3) specimens, usually with a surface crack length (a) of 35% of the specimen width (W). Fatigue precracking which was formerly to DD19(3) has more recently adhered to the requirements of BS5762:1979(4) and where possible

E813-81(5). During each test the load (P) and clip gauge displacement were autographically recorded as a function of the crosshead displacement (Δ) to permit both J integral and crack opening displacement parameters to be evaluated. The crosshead displacement rates employed were in the range 0.04 to 0.08mm/s. Following the test the specimens were heat tinted for 25 mins at 450^{0}C or 10 mins at 500^{0}C and broken open for crack length measurements. The initial crack length (a) stretch zone width (SZ) and true (fibrous) slow crack growth (Δa) were measured at 9 evenly spaced positions across the specimen thickness, including the two surfaces but unlike E813-81(5) were averaged over the 7 inner positions only. For each test using the SENB 3/ specimen type, the J-integral was evaluated from the area under the load/load point displacement plot up to the point of unloading (corrected for indentation and load train compliance) using the equation given by Sumpter and Turner(6) for crack lengths less than 50% of the specimen width:-

$$J = \frac{\eta e Ue + \eta p Up}{B(W-a)}$$

where Ue and Up are respectively the elastic and plastic components of the area under the load/load point deflection curve

B is the specimen thickness

ηe and ηp are geometry dependent constants ($\eta p = 2$ for the SENB geometry)

and the crack length (a) was averaged over the seven inner measurement positions.

The tests on SENB specimens differ from the ASTM procedure(5) in a number of ways. Apart from the shorter crack length/specimen width ratio (a/W), the difference between individual crack length measurements and the average crack lengt is usually greater than the 7% maximum as required by E813-81(5), although in most instances they satisfy the requirements of the UK COD standard(4). Also, particularly for Charpy sized specimens (B = W = 10mm), and the thickness B and ligament (W-a) are frequently smaller than the ASTM(5) specimen size requirements:

$$B, W-a, > 25\ J_{Ic}/\sigma_f$$

and $$B, W-a, > 15\ J/\sigma_f$$

where the flow stress σ_f is the mean of proof and ultimate stresses. Direct measurement of the true fibrous crack growth (Δa) permits the initiation J-integral (Ji) to be obtained from the extrapolation to $\Delta a = 0$ of a multi-specimen J/true Δa resistance line. All test data for Δa values between 0 and that corresponding to the achievement of maximum load are included in the resistance line and the 0.15 and 1.5mm exclusion lines of the ASTM procedure(5) are not used. Where it is difficult to distinguish between true fibrous crack growth and crack blunting, use is made of a blunting line which, for stainless steels, is of the form:-

$$J = 4\sigma_f\ \Delta a_{SZ}$$

where Δa_{SZ} is the crack growth including stretch zone.

This experimentally determined value is consistent with the findings of Mills(7) and Balladon et al(8).

3. TEST RESULTS

Extensive tests have been made on a 51mm thick plate of wrought Type 316 steel(P1) of composition given in Table 1 and on three 17Cr-8Ni-2Mo weld metals (W1, W8 and W23) of the compositions given in Table 1 in the form of 51mm thick, restrained single 60° V or 30° K preparations using the same main electrode batch.

3.1 Baseline Materials Tests

Wrought Type 316 steel P1 in a 2h 650°C heat treated condition has been tested at temperatures of 20°C, 250°C, 370°C and 550°C using SENB3 specimens of B = W = 10, 20 and 50mm, in all cases with a crack depth (a)/specimen width (W) ratio of ~ 0.4. In addition B = W = 50mm specimens of a/W = 0.5, with side-grooving depths of 12.5%, 25% and 50% have also been tested at 370°C. The results of these tests, which include re-analysis of tests by Chipperfield(9) are given in Figs 1 to 4. Comparison of Figs 1 to 4 shows that the initiation toughness decreases significantly from 20°C to 250°C but that from 250°C to 550°C there is little change in initiation toughness. The initiation J (Ji) and equivalent Ki values calculated from $K^2_i = EJi/(1-\nu^2)$ are listed in Table 2 and the corresponding tensile and Charpy impact data in Table 3. A marked fall in toughness between 20°C and 370°C also occurs for Type 316 weld metal (Fig 5); the respective Ji and equivalent Ki values are again listed in Table 2 and the tensile and Charpy impact data in Table 3.

The bulk of testing on weld metal has been at 370°C; a re-analysis of the tests made by Chipperfield(9),in Fig 6,shows the effect of post weld heat treatments on the toughness of Type 316 weld metal W1. Post weld heat treatments of 2h at 650°C or 850°C have no significant effect on the toughness relative to the as-welded state, however a solution treatment of 2h at 1050°C appreciably increases the toughness which approaches that of Type 316 steel. The initiation J and equivalent K_i values are again listed in Table 2 and the tensile/Charpy data in Table 3. The results of a range of tests at 370°C on weld metals W1, W8 and W23 heat treated for 2h at 850°C,using 10mm and 20mm specimens of a/W = 0.4 and side-grooved and unside-grooved 50mm specimens of a/W = 0.5 are shown in Fig 7. A comparison of Figs 3 and 7 shows that the initiation toughness (Ji) of 17-8-2 weld metal (40 to 50kJm^{-2}) at least a factor of 2 lower than for wrought Type 316 steel (Ji $\simeq$ 100 kJm^{-2}); the resistance curves, however, become very similar beyond about 1mm of crack growth.

The J/Δa relationship does not appear to be influenced significantly by the specimen size. The results indicate that provided the crack growth is less than about 8% of the remaining ligament then there is good agreement in J/Δa behaviour between different sizes of specimen even with differences in crack length and side-grooving. However, because the J/Δa relationship is not linear (eg Figs 2, 3 and 7) the initiation toughness may appear to be specimen size dependent. For example, the 10mm specimen test results are in effect confined to the steep (low crack growth) region of the J/Δa relationship; the use of a linear regression line for the 10mm specimen data will therefore tend to give a higher slope (dJ/da) and lower initiation value (Ji) than for larger specimens which also sample the higher crack growth region of the relationship.

3.2 Effects of Thermal Ageing

A number of tests have been made using B = W = 10mm SENB 3 specimens of a/W = 0.4 to study the effect of thermal ageing on Type 316 steel and weld metal. The thermal ageing was carried out on machined specimens, following precracking, by encapsulating the specimens in silica tubes filled with low pressure argon. These tests have examined two exposure temperature ranges: > 550°C and 370° to 450°C to give an accelerated representation of core outlet temperatures (∿ 540°C) and the sodium cold pool temperature (∿ 370°C) of the core support structure. A more extensive programme is in progress to study the effects on fracture toughness of long term thermal ageing in both high and low temperature ranges. Ageing times to over 40,000h at 400°C, 450°C, 550°C and 600°C are to be studied and the materials are, in general, in the form of un-machined blocks. As-welded weld metals representative of the extremes of δ ferrite content possible within the specification for the 17-8-2 material will be included in the low temperature range to examine any tendency for embrittlement due to the formation of α' phase.

3.2.1 High temperature ageing (> 550°C)

Two ageing conditions have been examined in the higher temperature range: 9000h at 650°C and 30,000h at 625°C with specimens being tested at 550°C in both cases. For the higher temperature ageing, three material conditions were studied, Type 316 steel (P1) and weld (W1) heated treated for 2h 650°C and Type 316 weld (W1) heat treated for 2h 850°C. For the 30,000h 625°C ageing treatment, only 2h 650°C heat treated Type 316 steel and 2h 850°C heat treated weld (W1A) were examined. The effect of these high temperature ageing treatments on the toughness of Type 316 steel at 550°C is shown in Fig 8. Both 9,000h/650°C and 30,000h/625°C ageing treatments adversely affect the toughness of Type 316 steel with the initiation toughness (Ji) falling from 87 kJ/m^2 unaged to 39 kJ/m^2 following ageing (see Table 2). Figure 9 shows the equivalent effect on weld metal; neither ageing treatment had a significant effect on the toughness of weld metal at 550°C although it should be noted that the scatter band for the unaged material W1/W1A was quite wide. The tensile and Charpy impact data for the aged materials are given in Table 3.

3.2.2 Low temperature ageing (370°C to 450°C)

A number of toughness tests at 370°C have been completed on Type 316 steel and weld metal aged for relatively short times in the temperature range 370°C to 450°C. Figures 10 and 11 respectively, show the effect of ageing for 13,000h at 370°C and 1000h at 450°C on the toughness of Type 316 steel P1 in the 2h 650°C heat treated condition; neither ageing treatment causes a significant change in the fracture toughness. A similar pattern of behaviour is also observed for Type 316 weld metal in the 2h 650°C heat treated condition. Figures 12 and 13 show the effect of ageing for 13,000h at 370°C and 1340h at 420°C respectively on the toughness of weld metal; again very little difference between the aged and unaged materials is evident.

4. DISCUSSION

The majority of specimens used do not meet the requirements of the ASTM E813-81(5) procedure for determining the initiation J integral toughness J_{IC}. In particular the B = W = 10mm specimens are outside the validity limits for specimen size, crack length and crack front curvature but for a common crack growth range they show virtually identical behaviour to larger side-grooved specimens which meet the requirements of E813-81(5) (Figs 3 and 7). These results justify the extensive use of 10mm specimens to study aspects of the fracture toughness of Type 316 steel and weld metal, although for a small number of data points per condition subtle changes in toughness may be masked by scatter in the data.

The marked change in fracture toughness of Type 316 steel between room temperature and 250°C with little change between 250°C and 550°C, and the similar change for weld metal between 20°C and 370°C is consistent with the tensile properties (Table 3). The strength (particularly UTS), work hardening capacity and ductility fall markedly between 20°C and 250°C. The change in ductility will be reflected in a corresponding change in the crack tip ductility represented by the crack opening displacement δ; the J integral will additionally be dependent on the yield stress in the relationship:-

$$J \propto \sigma_y \delta$$

where σ_y is the yield stress.

Although a 2h 650°C or 2h 850°C post weld heat treatment reduces the strength of Type 316 weld metal, the ductility and work hardening capacity are somewhat increased by these treatments; the net effect is to leave the toughness effectively unchanged. A solution heat treatment for 2h at 1050°C however very much increases the ductility (particularly elongation) and also increases the work hardening capacity, by reducing the yield stress, without greatly affecting the UTS. In this instance the increase in ductility and work hardening capacity is sufficient to substantially increase the initiation fracture toughness and tearing resistance. Ageing Type 316 steel at 625°C or 650°C increases the yield strength while very much reducing the ductility and work hardening capacity of the material; the effect is to very markedly reduce the fracture toughness of the aged materials relative to the unaged condition. Fractographic examination of the 9000h/650°C aged steel has shown that fine ductile microvoids are formed around the $M_{23}C_6$ carbide precipitates formed during the ageing treatment. Neither the tensile nor the toughness properties of Type 316 weld metal are appreciably affected by high temperature ageing.

Although tensile and Charpy properties are not yet available for the low temperature thermal ageing conditions it seems likely that the diffusion controlled precipitation mechanisms will occur too slowly to cause any appreciable change in properties in the relatively short timescale of the thermal ageing treatments. In addition the δ-ferrite content of the Type 316 weld metal following a 2h 650°C heat treatment is quite low so that embrittlement by the formation of α' phase, 3.5 to 6.5%, may not be noticeable. A more extensive examination of as-welded material containing up to 9% δ-ferrite should reveal any embrittlement problems arising from this mechanism.

5. CONCLUSIONS

1) For crack growth of not greater than 8% of the remaining ligament the J/Δa relationship for a material is not affected by the specimen size, despite wide deviations from the requirements considered necessary for J-controlled growth.

2) The initiation toughness (Ji) of Type 316 weld metal is over a factor 2 lower, or as Ki about 40% lower, than that of Type 316 steel at the same temperature.

3) The fracture toughness of both Type 316 steel and weld metal falls appreciably from 20°C to 250/370°C.

4) The initiation toughness (Ji) of Type 316 weld metal is unaffected by 2 hour post weld heat treatments at 650°C or 850°C but is increased by over 70% and Ki by over 45% by a 2h 1050°C heat treatment; the toughness of 2h 1050°C heat treated weld metal approaches that of wrought steel.

5) High temperature (625°C or 650°C) thermal ageing reduces the toughness of Type 316 steel to a level similar to weld metal, an effect caused by carbide precipitation. The same ageing treatment does not significantly affect the toughness of Type 316 weld metal.

6) Low temperature thermal ageing (370°C to 450°C) for relatively short times does not significantly affect the toughness of either Type 316 steel or 2h 650°C PWHT weld metal.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

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TABLE 1. MATERIAL DETAILS

Material Identn.	Material	Thickness (mm)	Weld Preparation	Composition wt.%									
				C	Mn	Si	Cr	Ni	Mo	S	P	B	N
P	Wrought Type 316 steel Heat No 13678.	51	-	0.054	1.8	0.56	16.5	10.8	2.3	0.023	0.033	0.0028	0.043
W1	17-8-2 MMA Weld 105/1	51	60° V	0.068	2.09	0.35	18.0	9.5	1.73	0.014	0.023	< .005	N/A
W1A	17-8-2 MMA Weld 105/1/2	51	30° K	0.073	1.9	0.43	18.1	9.8	1.70	0.013	N/A	0.0003	0.048
W8	17-8-2 MMA Weld 540/1	51	60° V	0.064	2.00	0.27	17.9	9.5	1.62	0.011	0.023	< .005	N/A
W23	17-8-2 MMA Weld 738/ 40/41	51	60° V	0.068	1.94	0.33	17.8	9.5	1.68	0.014	0.022	< .005	N/A

N/A indicates analysis not available.

TABLE 2. THE TOUGHNESS PROPERTIES OF THE TYPE 316 STEEL AND WELD METALS STUDIED

Material	Heat Treatment	Test Temp (°C)	Specimen Size B, W (mm)	Initiation J Integral Ji (kJ/m^2)	Resistance Curve Slope dJ/da (N/mm^2)	Tearing Modulus T	Approx Young's Modulus E (N/mm^2)	Equivalent Fracture Toughness Ki (MPa√m)+
P1	ST + 2h 650°C	20	10,20,50	290*	∿ 200*	∿ 494	1.98×10^5	240
P1	" "	250	10,20,50	83*	341*	1080	1.81×10^5	128
P1	" "	370	10,20,50	108*	205*	640	1.71×10^5	142
P1	" "	550	10,20,50	94*	172*	808	1.59×10^5	128
P1	" "	550	10	87	200	939	1.59×10^5	123
P1	ST + 2h 650°C + 9000h 650°C) ST + 2h 650°C + 30,000h 625°C)	550	10	39	204	480	1.59×10^5	83
W1 & W1A	As welded	20	10	85	359	224	1.58×10^5	121
W1	" "	370	10	47	155	131	1.35×10^5	84
W1	As welded) 2h 650°C) 2h 850°C)	370	10	41	202	170-400	1.35×10^5	78
W1	2h 1050°C	370	10	70	428	2160	1.71×10^5	115
W1 + W8 + W23	2h 850°C	370	10,20,50	42*	229*	454	1.35×10^5	79
W1	2h 650°C	550	10	25	313	526	1.26×10^5	59
W1 W1 W1A	2h 650°C + 9000h 650°C) 2h 850°C + 9000h 650°C) 2h 850°C + 30,000h 625°C)	550	10	31	202	460	1.26×10^5	66

* values from linear regression line through data points up to 0.4mm crack growth

$^+Ki = (E\ Ji/1-\nu^2)^{0.5}$

ST denoted solution treatment.

TABLE 3. TENSILE V NOTCH AND CHARPY IMPACT DATA FOR THE MATERIALS STUDIED

Material	Heat Treatment	Temp (°C)	0.5% PS (N/mm^2)	UTS (N/mm^2)	Total Elongation (%)	Uniform Elongation (%)	Reduction of Area %	V Notch Charpy Impact Energy (J)
P1	2h 650°C	20	283	628	71	60	68	120
P1	" "	250	239	504	44	38	52	89
P1	" "	370	234	487	44	27	57	80
P1	" "	550	184	472	45	37	50	81
P1	2h 650°C + 9000H 650°C	550	250	479	23	16	32	46
P1	2h 650°C + 30,000h 625°C	550	269	481	30	26	36	45
W1/W1A	As welded	20	482	662	38	28	53	-
W1	" "	370	399	485	16	12	31	71
W1	2h 650°C	370	286	431	22	16	35	69
W1	2h 850°C	370	261	423	22	16	43	87
W1	2h 1050°C	370	184	449	35	24	44	125
W1	2h 650°C	550	276	375	20	14	48	-
W1	2h 650°C + 9000h 650°C	550	250	395	22	16	38	50
W1	2h 850°C + 9000h 650°C	550	226	377	20	15	45	69
W1A	2h 850°C + 30,000h 625°C	550	230	390	23	19	51	39

Fig 1 Fracture toughness of Type 316 steel P1 at 20°C.

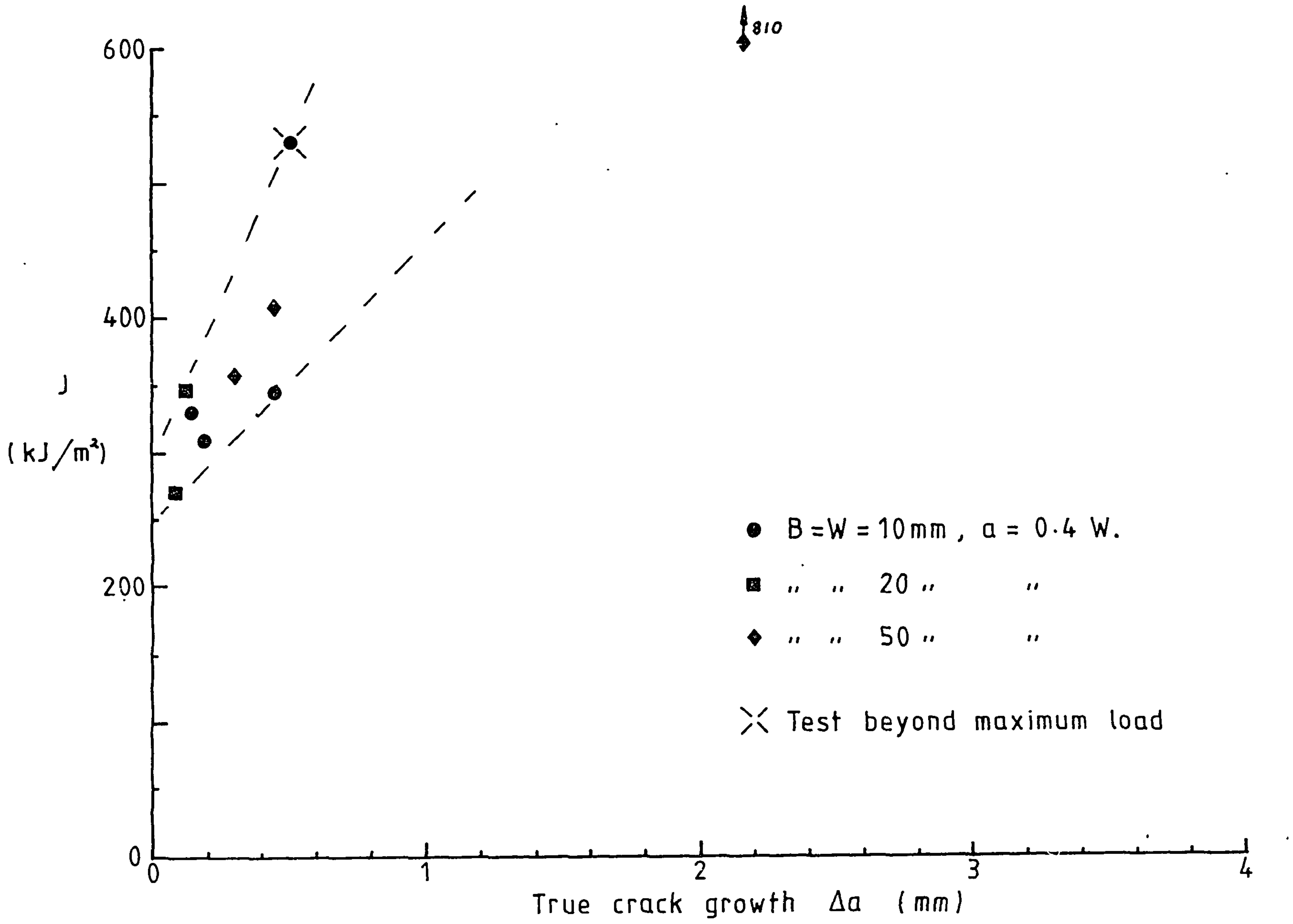


Fig 2 Fracture toughness of Type 316 steel P1 at 250°C.

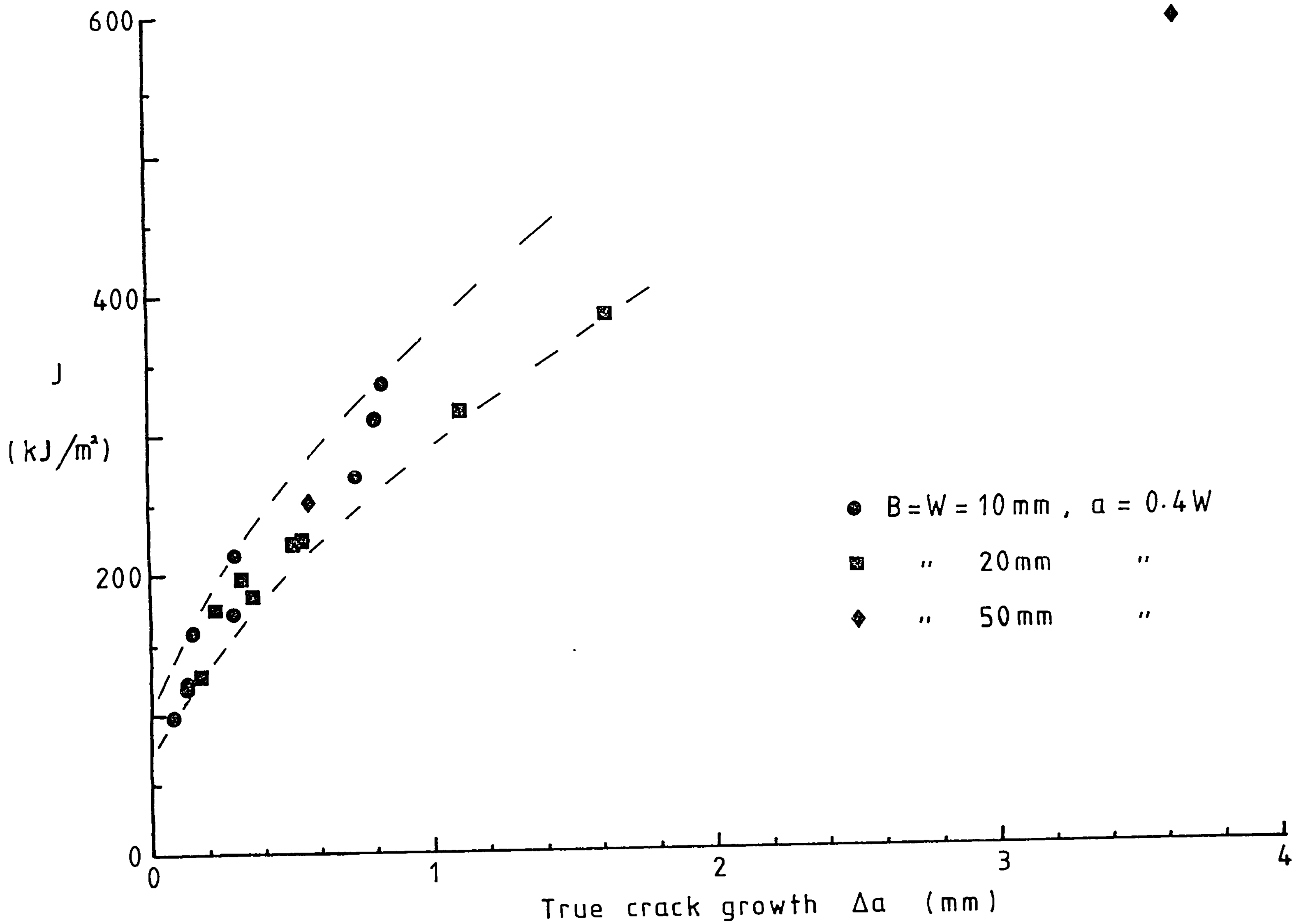
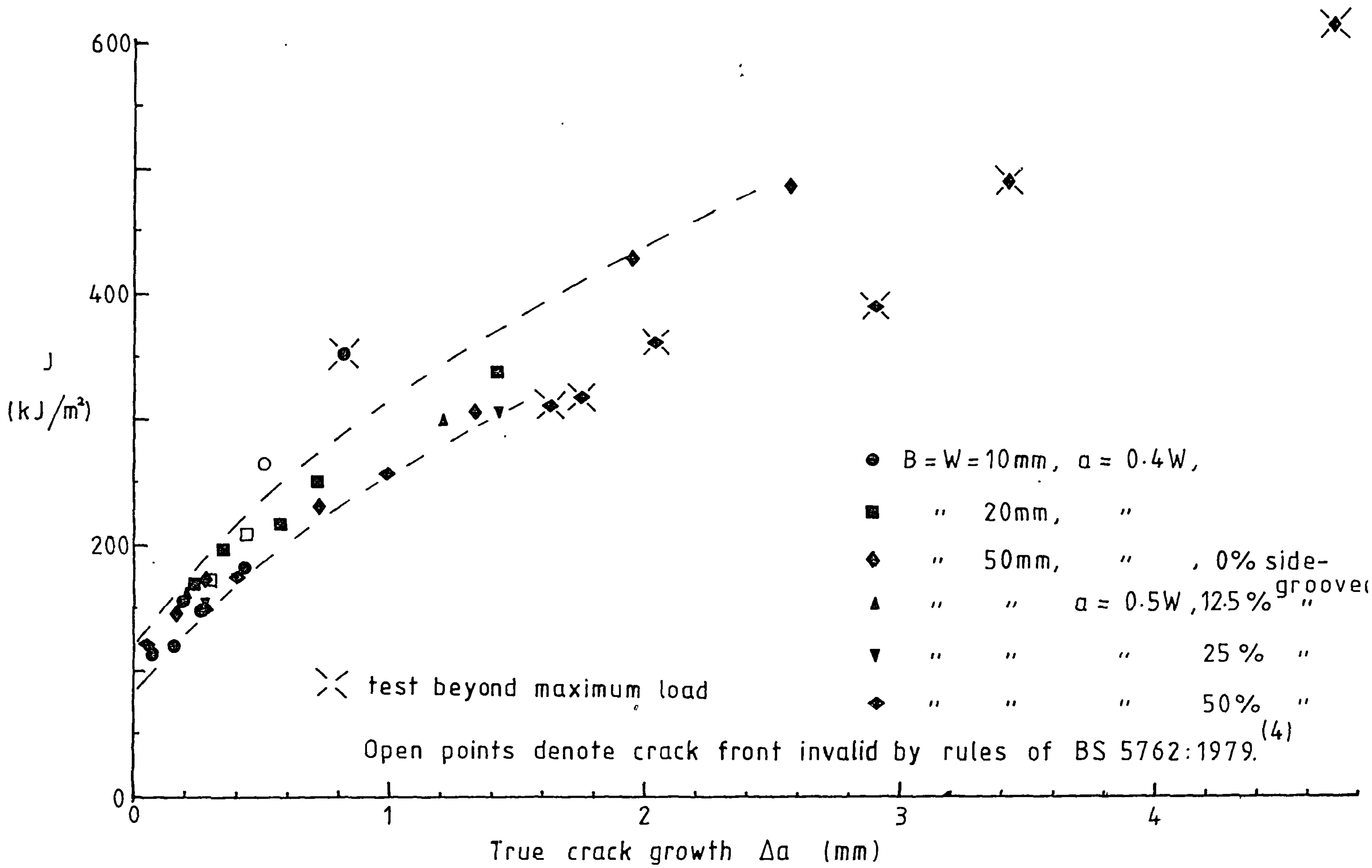


Fig 3 Fracture toughness of Type 316 steel P1 at 370°C.



Open points denote crack front invalid by rules of BS 5762:1979.(4)

Fig 4 Fracture toughness of Type 316 steel P1 at 550°C.

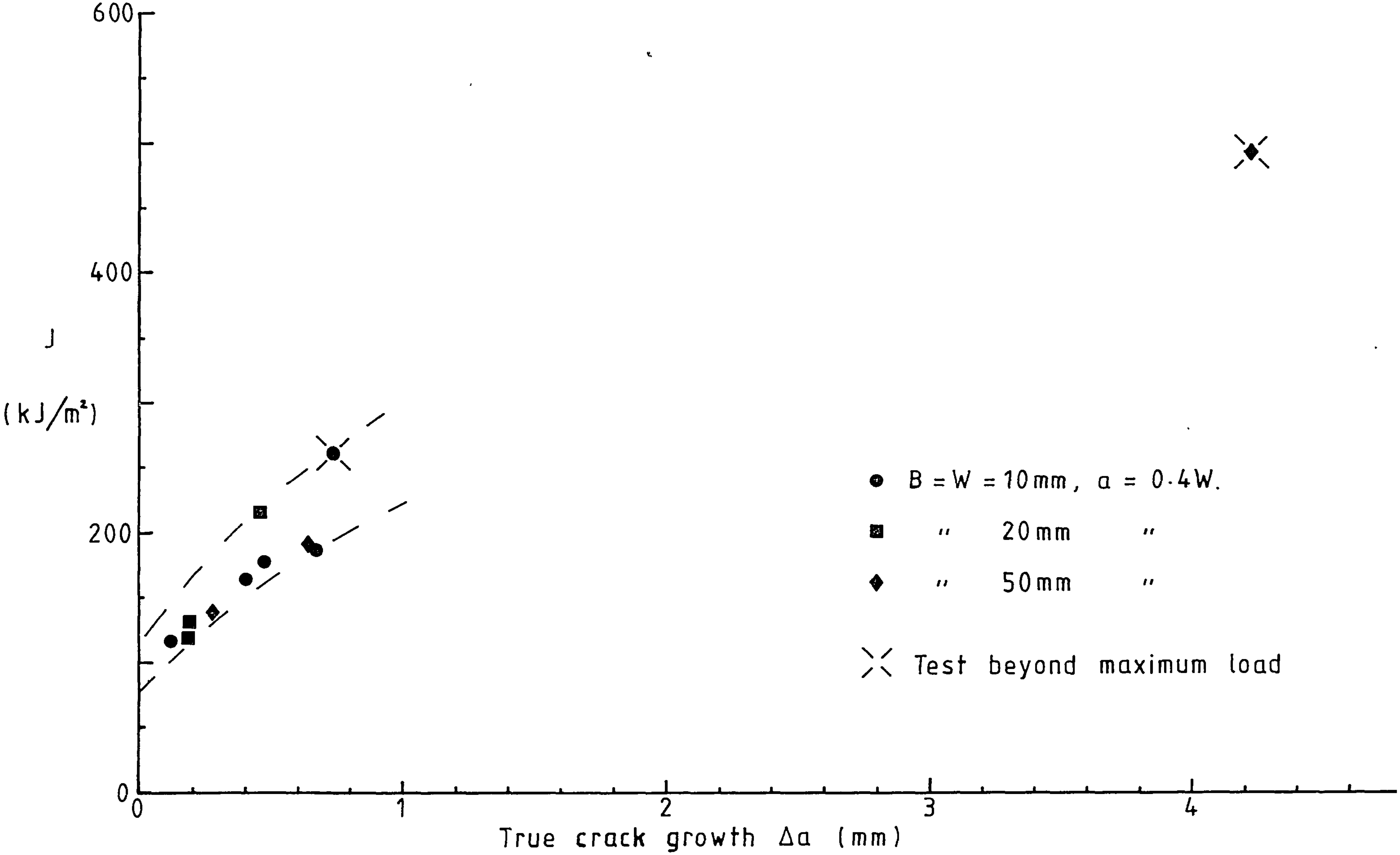


Fig 5 Comparison of fracture toughness of as-deposited Type 316 weld metal at 20°C and 370°C; 10mm specimens.

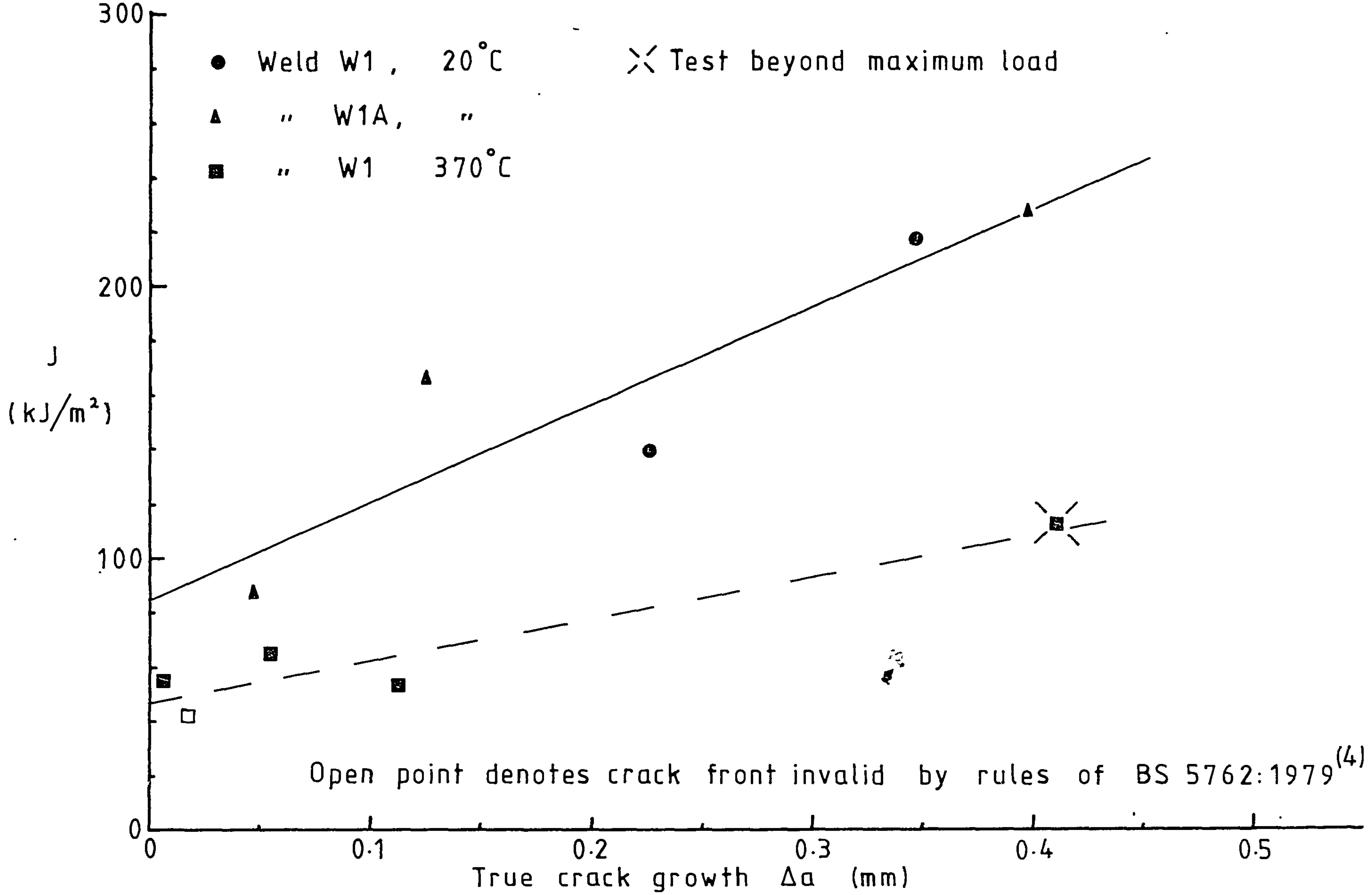


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Fig 6 Effect of post weld heat treatment on the fracture toughness of Type 316 weld metal W1 at 370°C, 10mm specimens.

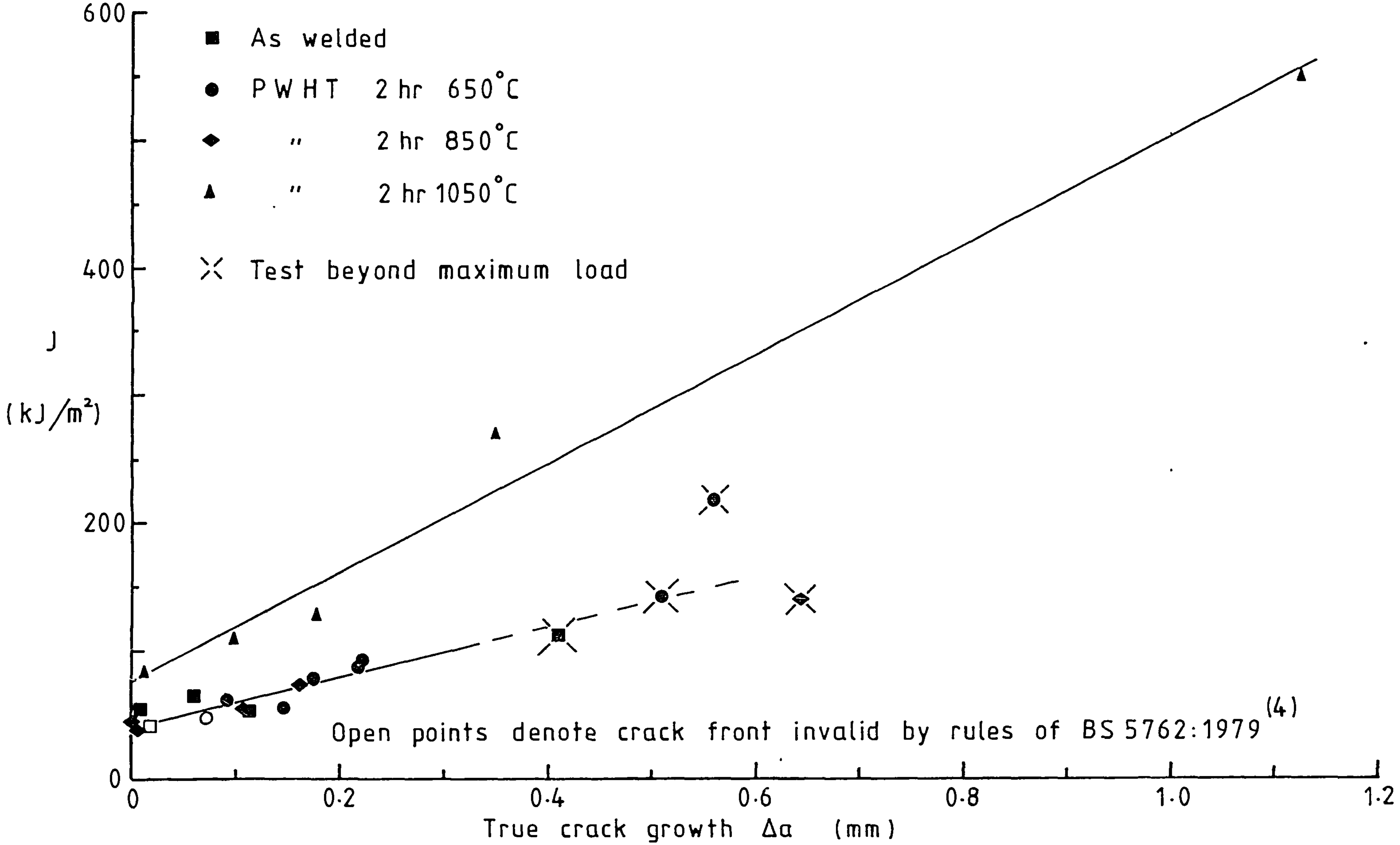

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Fig 7 Fracture toughness of Type 316 weld metal PWHT 2hr 850°C.
Test temperature 370°C.

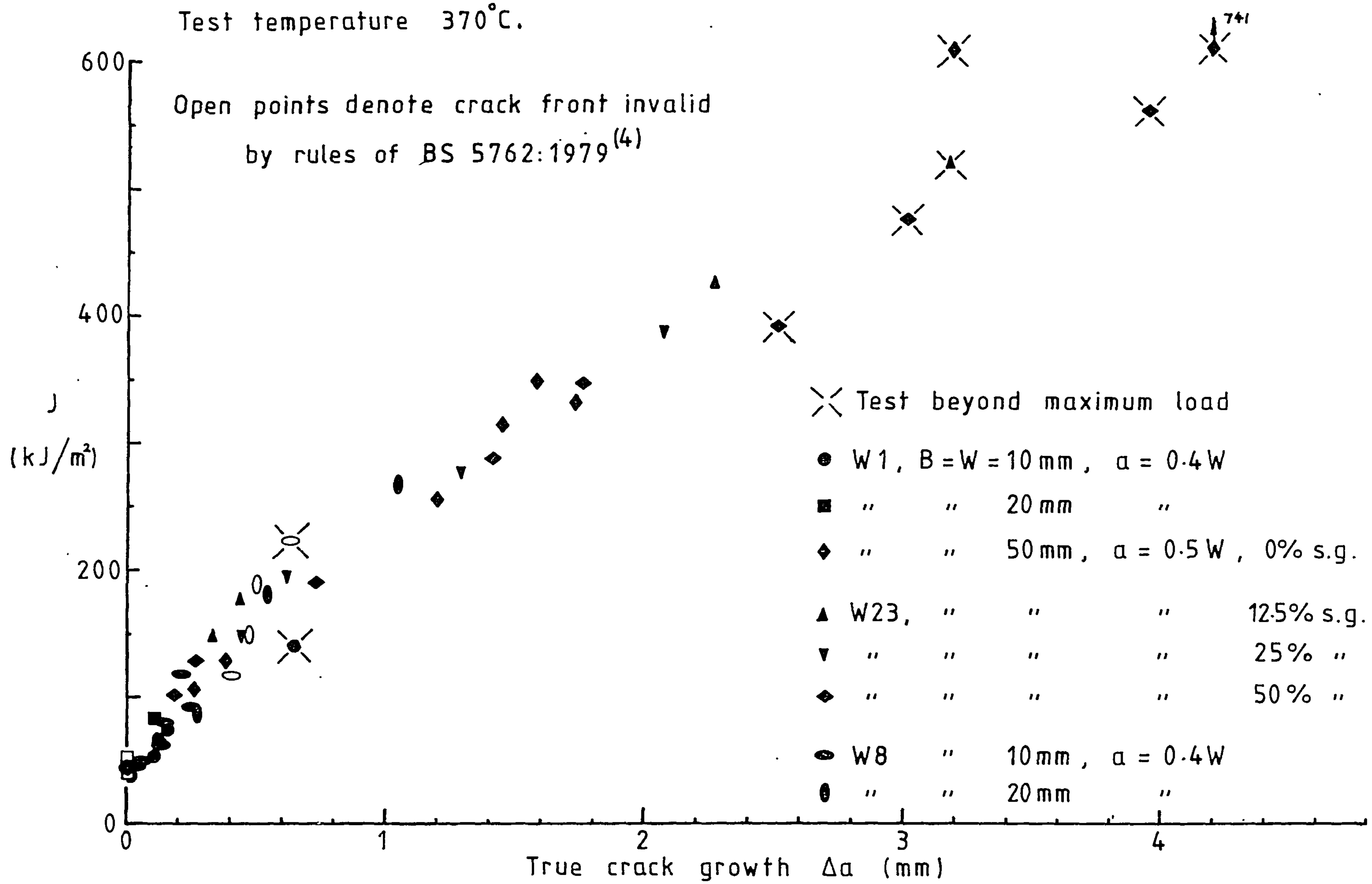


Fig 8 Effect of high temperature ageing on the fracture toughness of Type 316 steel P1 at 550°C, (10 mm specimens)

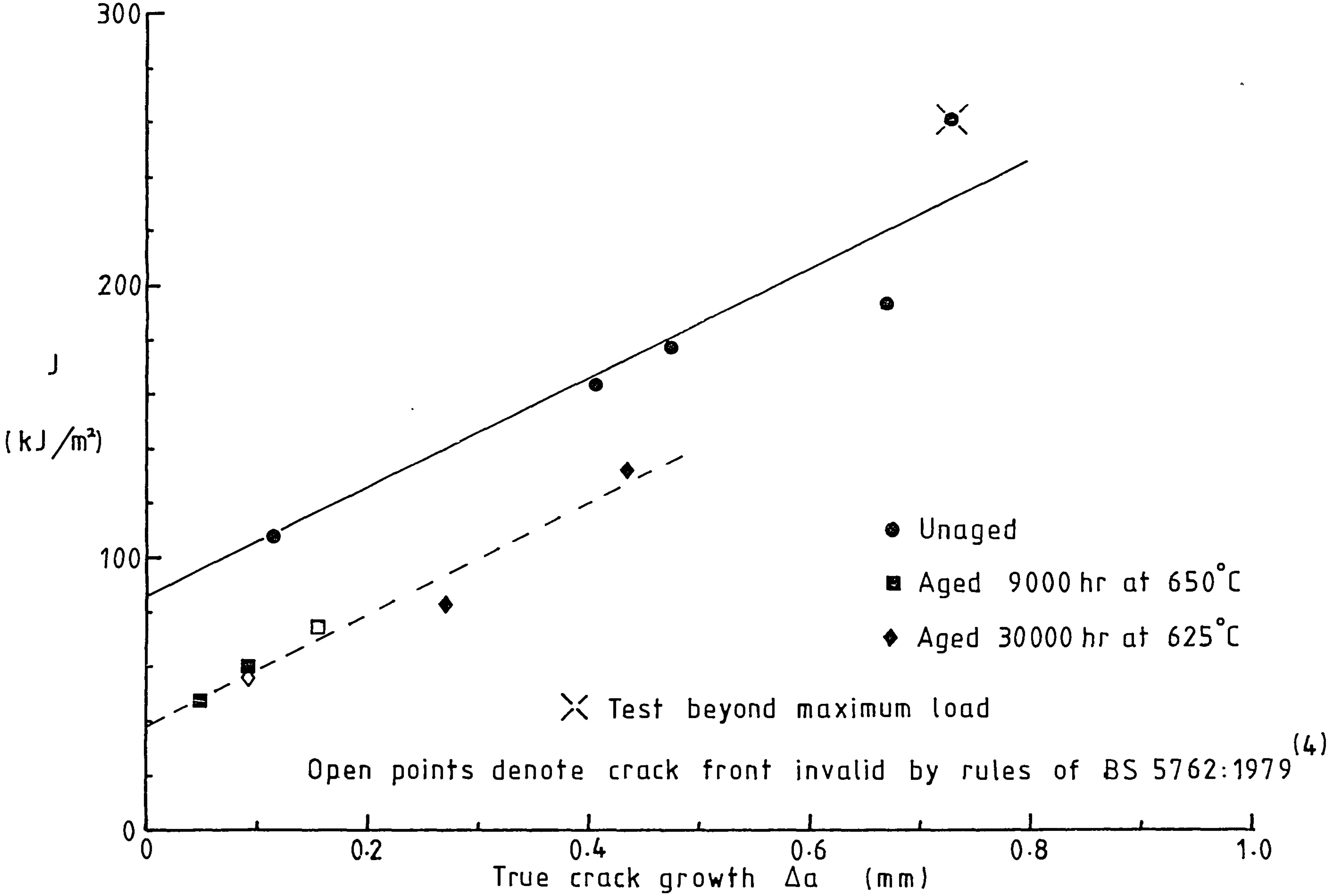


Fig 9 The effect of high temperature ageing on the fracture toughness of Type 316 weld metal at 550°C, (10 mm specimens)

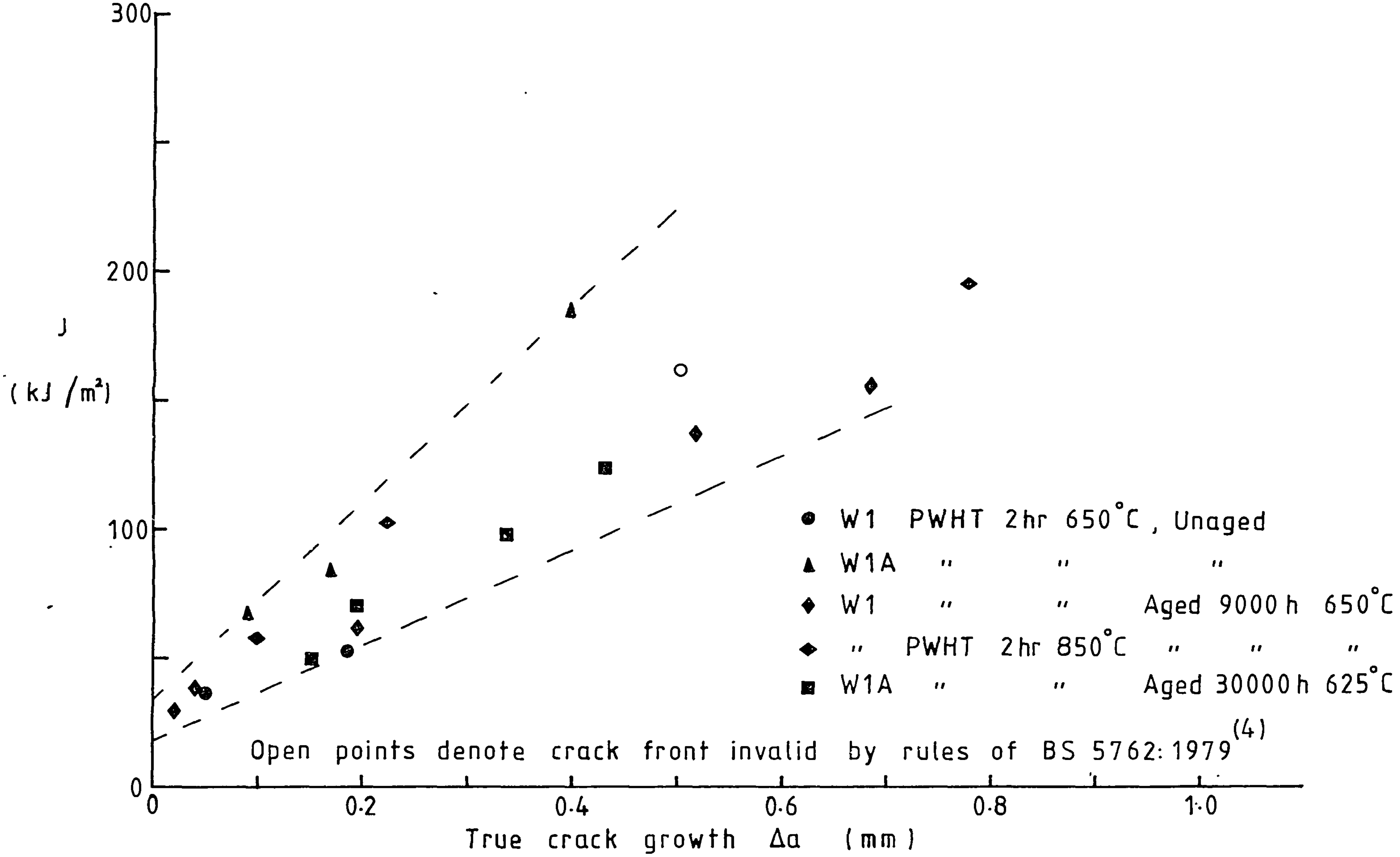
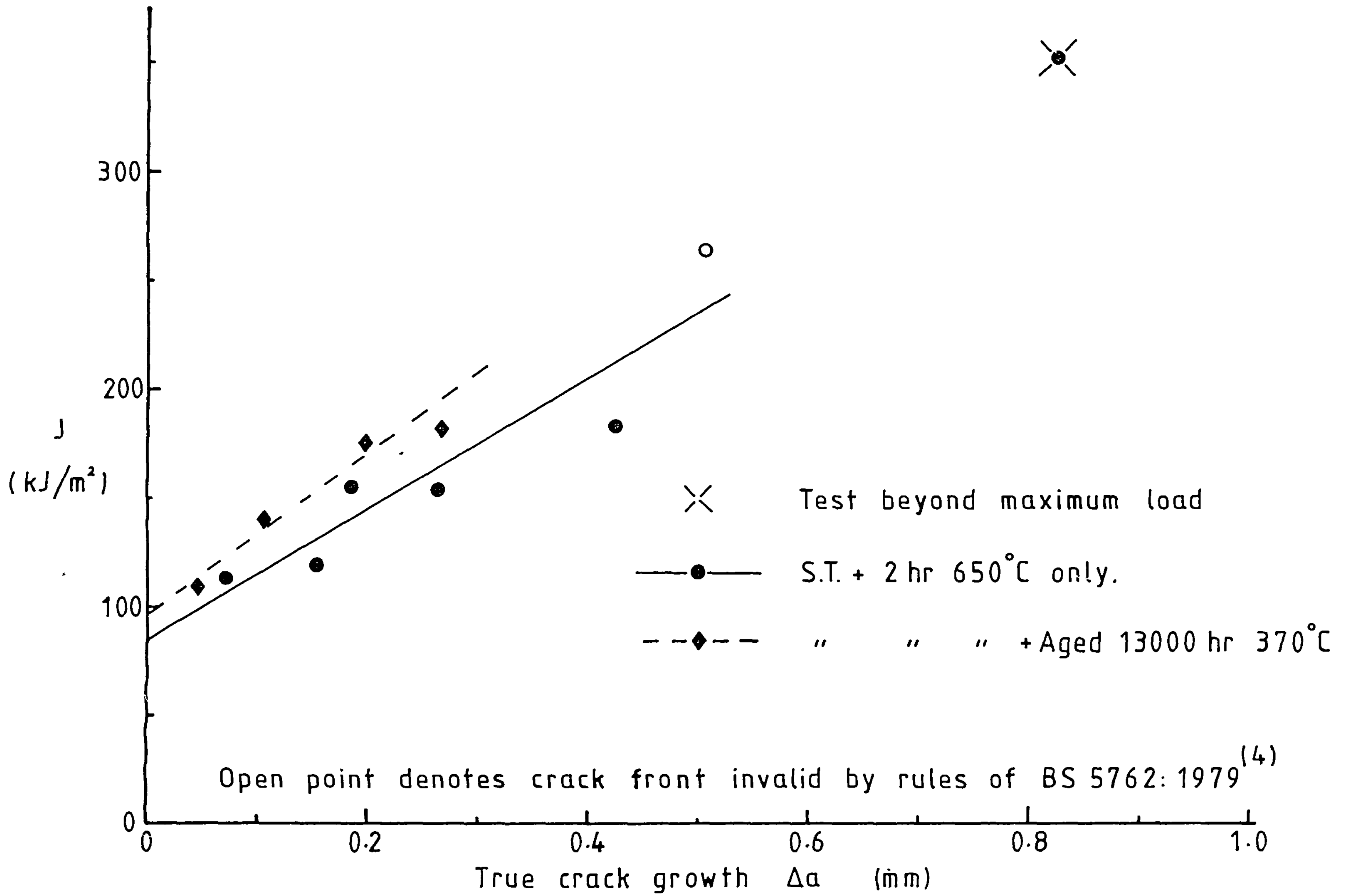


Fig 10 The effect of ageing for 13000 hrs at 370°C on the fracture toughness of Type 316 steel P1 at 370°C. (10 mm specimens).



Open point denotes crack front invalid by rules of BS 5762: 1979 (4)

Fig 11 The effect of ageing for 1000 hrs at 450°C on the fracture toughness of Type 316 steel P1 at 370°C (10 mm specimens)

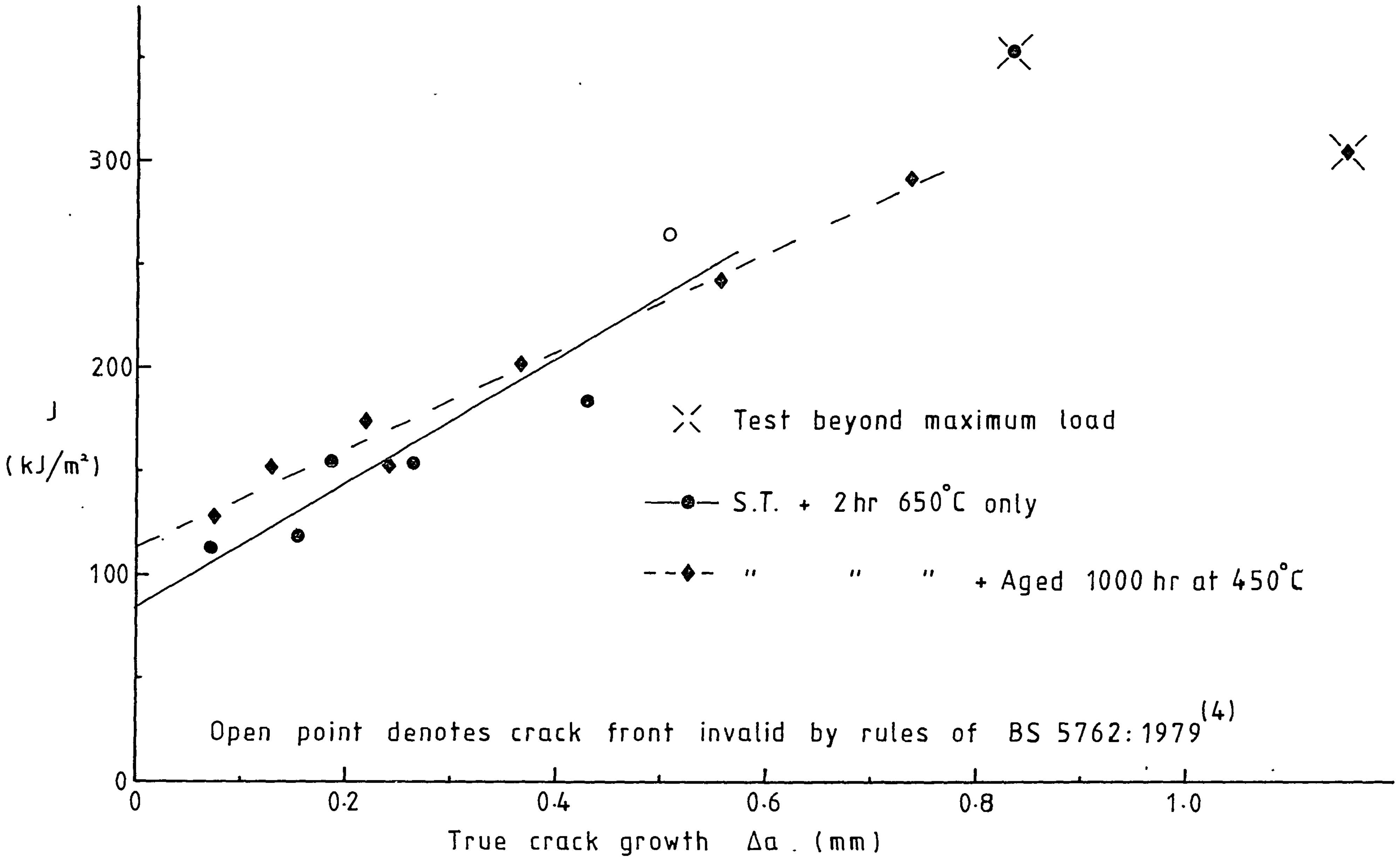


Fig 12 The effect of ageing for 13000 hrs at 370°C on the fracture toughness of Type 316 weld metal at 370°C.

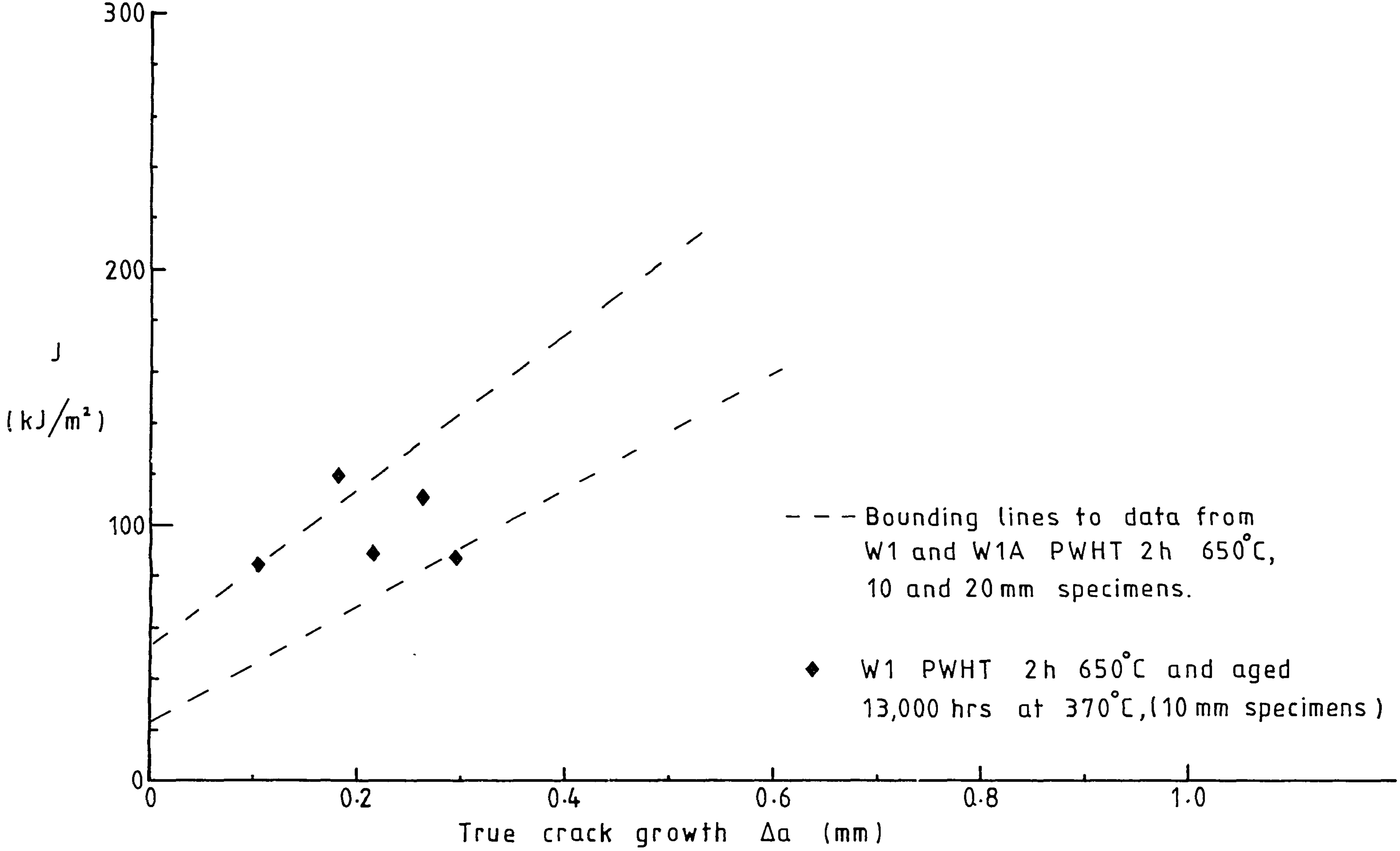
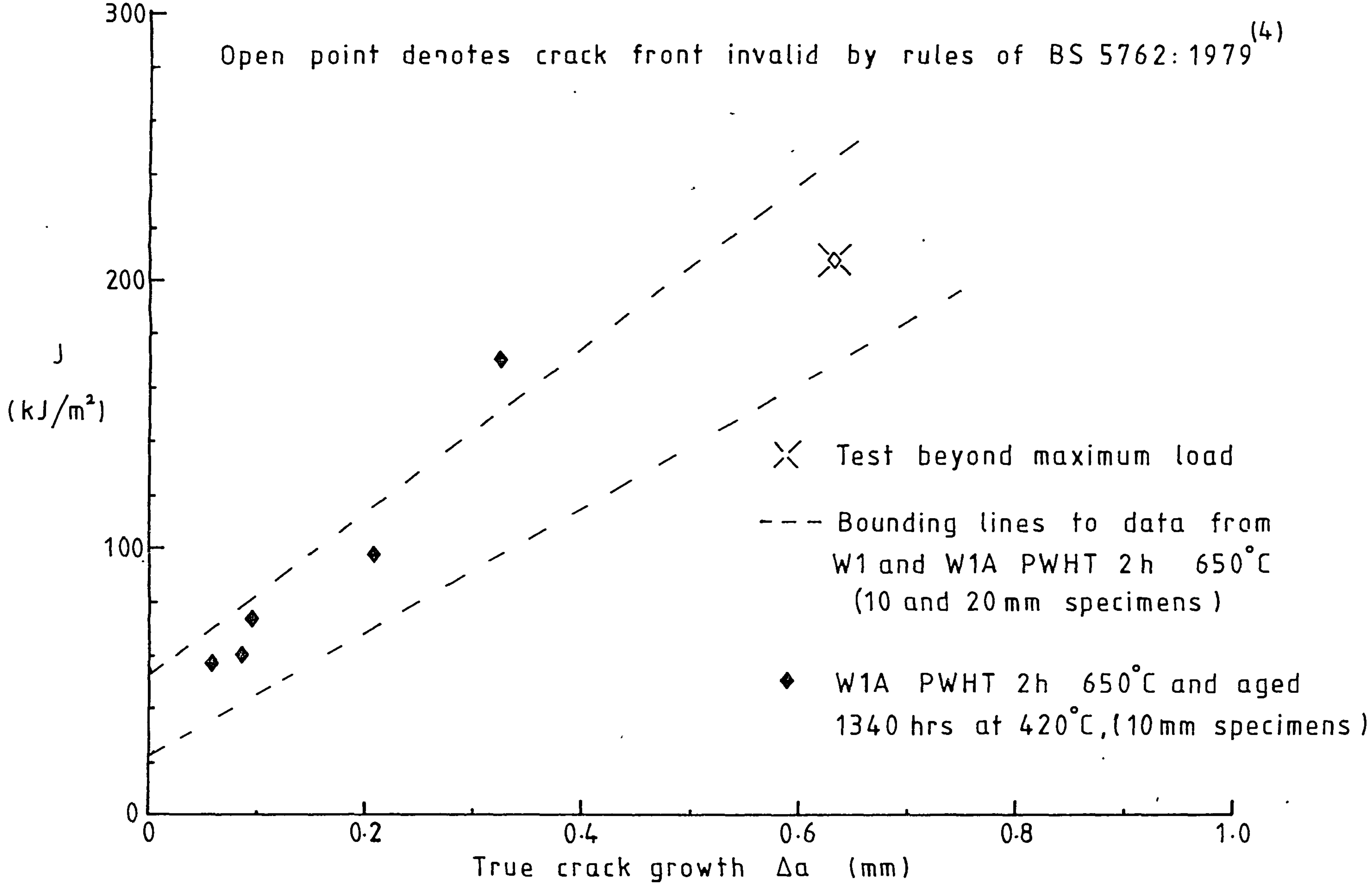


Fig 13 The effect of ageing for 1340 hrs at 420°C on the fracture toughness of Type 316 weld metal at 370°C.


Open point denotes crack front invalid by rules of BS 5762: 1979(4)