HIGH STRENGTH STEEL WELDMENTS FUSION BOUNDARY NOTCH TOUGHNESS

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Low values of notch toughness have been observed in the coarse grained zone of the HAZ of steel weldments. The present investigation focused on the influence of the welding process heat input on the extent and notch toughness properties of the fusion boundary zone of the HAZ. A correlation was established between cooling time in the HAZ, microstructure in the fusion boundary zone and notch toughness properties.

INTRODUCTION

The heat affected zone of a welded steel joint presents a gradient of microstructures from the fusion boundary to the unaffected base material. Four main regions have been identified in the HAZ by Thaulow et al (1):

- A coarse grained zone, near the fusion boundary where the peak temperature, T_p, induced by the welding thermal cycle is in excess of 1150 °C.
- A fine grained zone with $870 < T_p < 1150$ °C
- A partly transformed zone where $700 < T_p < 870$ °C
- A tempered zone with $T_p < 700$ °C.

Low values of the notch toughness have been observed in the coarse grained zone both in the as welded and post welded heat treated condition, mainly in joints produced with high heat input processes as reported by Pisarski et al (2), Dolby (3) and Bufalini (4). Since these brittle zones can extend to the surface of the welded joint it is important to examine whether unstable fracture

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can be initiated from shallow surface cracks or defects frequently found in these zones.

The coarse grained zone is generally considered to be the zone with the lowest toughness although in some cases lower values can occur in the subcritical HAZ as referred by Dolby and Saunders (5) Szydlik (6) and Satoh et al (7).

The aim of the present investigation was to study the influence of the welding process heat input on the notch toughness properties of the coarse grained zone of the HAZ of a high strength steel welded joint. A correlation was established between the microstructure and notch toughness properties.

MATERIALS AND EXPERIMENTAL PROCEDURE

Welded coupon plates of a StE 36 - SEW 089 steel, 12 mm thick were produced with the submerged arc welding (SAW). The chemical composition and mechanical properties of the base material are given in table 1.

TABLE 1 - Chemical composition and mechanical properties of base material

%C	%Si	%Mn	%P	%S	%Al
0.19	0.22	1.15	0.019	0.015	0.05

Yield point N/mm^2	U.T.S. N/mm^2	Elongation (5d) %	Impact (DVM) "J"(Trans.-20°C)
397	541	30	56-62

As filler metal the couple wire/flux AWS EL12-F70 was used.

Bead on plate welds were deposited with heat inputs varying from 1 to 4.5 KJ/mm.

Weld thermal cycles were measured with three Ni-NiCr thermocouples attached to the plates near the fusion boundary and recorded by means of a computer.

The thermal cycle was characterized by means of the parameter Δt 8/5 (s) (cooling time from 800°C to 500°C).

The notch toughness of the coarse grained zone of the HAZ was evaluated by means of Charpy V and CTOD testing. Charpy V testing was carried out at several temperatures in order to obtain a transition curve and the CTOD testing was limited to -10^{o}C for economic reasons.

The weld beads were deposited perpendicularly to the rolling direction. The removal of the specimens and location of the notch is illustrated in Fig. 1.

Charpy V testing was carried out according to DIN 50115 standard and the CTOD testing according to BS 5762: 1979, using the subsidiary specimen geometry.

Quantitative metallography and fractographic analysis was also carried out on specimens removed from the welded plates.

RESULTS

Weld beads were produced for various heat inputs of the SAW. The weld thermal cycles used are presented in table 2. The Δt 8/5 parameter values indicated represent the average values of 3 attached thermocouples.

TABLE 2 - Weld thermal cycles measured during the production of the welded plates

Specimen N.	Heat Input KJ/mm	Δt 800/500^{o}C seconds
1	1.2	23
2	2.1	32
3	2.8	65
4	3.1	67
5	4.5	112
6	1.9	31
7	2.0	48
8	2.2	45
9	1.9	35

Specimens 6,7,8 and 9 were produced using approximately the same heat input, but with different welding parameters in order to examine the influence of the weld bead geometry on the weld thermal cycle and microstructure of the HAZ.

A typical weld thermal cycle is showed in Fig. 2. Fig. 3 illustrates a typical macrograph of one of the specimens produced.

Quantitative metallographic studies were performed in order to measure the grain size and constituent volume fraction in the coarse grained zone of the HAZ of each specimen.

The grain size was measured by the interception method: due to the gradient of microstructures present in the HAZ the method proposed in ASTM STP 504 (8) was used with slight modification. The grain size was evaluated by the interception of lines parallel to the fusion boundary. The results obtained are shown in Fig. 4, which correlates grain size with the cooling time Δt 8/5.

The evaluation of the constituent volume fraction of the coarse grained zone was carried out by a point counting technique according to ASTM STP 504. It is estimated that the measurement error was less than 5%. Fig. 5 presents the correlation constituent volume fraction cooling time. Fig. 6 and 7 show typical microstructures of the coarse grained zone of the HAZ of welds obtained with heat inputs of 1 and 4.5 KJ/mm respectively.

The notch toughness properties as measured by the Charpy V testing are shown in Fig. 8. CTOD testing at -10^{o}C was also performed, the results being presented in table 3 and Fig. 9. The specimens a/w ratio varied between 0.2 and 0.7. Due to the dimensions of the clip gauge used it was not possible to perform the test with a load span equal to 4W, the span used was 4.8W which is slightly above the value recommended in the BS 5762 standard. Thus, the stress intensity factor value, K, had to be corrected in order to calculate the δ values. The calibration expression used was in accordance with BS 5447: 1977 for bend test pieces.

Some of the specimens showed pop-in behaviour as illustrated in Fig. 10.

DISCUSSION

The coarse grained zone of the HAZ is very narrow which makes not only the measurement of the thermal cycles very difficult, but also the evaluation of the notch toughness properties. In fact the positioning of the thermocouples near the fusion boundary is critical. It was therefore necessary to use several thermocouples in order to obtain meaningfull records. Only thermal cycles with peak temperatures in excess of 1250^{o}C were considered adequate. It was observed that an increase of the heat input leads to an increase of the Δt 8/5 parameter, as can be seen in table 2. Nevertheless it was also found that the heat input may not be a suitable parameter to characterize the thermal cycle of a welded joint since for the same heat input different cooling times were obtained as indicated in table 2 for specimens 6 to 9. This is probably due to the influence of weld bead geometry which is similar to the effect observed in deposited weld metal by Rodrigues (9).

TABLE 3 - CTOD Values for grain coarsened region of HAZ

Specimen No	a/w	Vp (mm)	P (N)	COD (mm)	Type
1.1	0,247	1,18	9299	0,5	δm
1.2	0,212	0,96	10270	0,431	δu
	0,212	2,55	11021	1,167	δm*
2.1	0,453	0,54	4691	0,14	δm
2.2	0,553	2,46	3972	0,505	δm
3.1	0,482	1,1	4766	0,282	δm
3.2	0,545	0,5	3177	0,112	δu
	0,545	2,49	3624	0,518	δm*
4.1	0,518	1,9	3972	0,43	δm
4.2	0,376	1,2	6777	0,394	δm
5.1	0,7	2,1	1738	0,265	δm
5.2	0,517	0,86	3823	0,202	δu
6.2	0,305	1,98	8291	0,747	δm
7.1	0,229	0,25	8440	0,123	δu
	0,229	2,68	9235	1,177	δm*
7.2	0,254	0,45	7844	0,199	δu
	0,254	1,68	8639	0,706	δm*
8.1	0,44	0,04	4120	0,022	δc
	0,44	1,65	5610	0,46	δm*
8.2	0,412	1,46	6065	0,437	δm
9.1	0,4	1,79	6553	0,548	δm
9.2	0,38	0,46	6205	0,159	δu
	0,38	1,6	6404	0,512	δm*

* pop-in was followed by an increase of the load

In the present work a marked increase of the grain size near the fusion boundary was observed when the cooling time increased as clearly illustrated in figure 4 which is in accordance with the observation of others authors (10,11). In fact there was an increase of prior austenite grain size but also a coarsening of the micro constituents. Dolby et al (5) observed a similar effect in an aluminium treated C-Mn steel. This increase of grain size was also accompanied by a variation of the volume fraction of the micro-constituents present as can be seen in Fig. 5. The microstructure was composed mainly of primary ferrite, upper bainite and ferrite side plates. When the cooling time increased the volume fraction of the upper bainite (UP) decreased, with an increase of the grain boundary ferrite (GBF) and ferrite side plates (FSP).

The use of the Charpy V testing to measure the notch toughness of the fusion boundary zone revealed some limitations of this type of testing due to the difficulty of accurately locating the notch on the one hand and on the other hand due to the fact that in this test the absorved energy corresponds to initiation and propagation of an unstable fracture through a gradient of microstructures which can not be discriminated by this type of test. In fact the fractographic analysis of the fracture surface of some specimens revealed the occurrence of crack arrests during the propagation, as illustrated by Fig. 11,where a ductile zone surrounded by a cleavage fracture can be seen. The results presented in Fig. 8 show a wide scatter of results without revealing a clear correlation between the cooling time and the absorved energy. In this respect the CTOD testing is a more useful test since the fatigue crack tip can be located in the coarse grained zone and measures the energy to initiate an unstable fracture. In a fact a better correlation could be obtained as illustrated in Fig. 9, although some scatter is still observed with some results not following the main trend. In the cases where a pop-in occurred, followed by a load increase, values of δm were also calculated.

These values are given in table 3 for comparison purposes. It was also observed that even with CTOD testing some difficulty in locating the fatigue crack tip may occur, which can explain the scatter observed. The results obtained seem to indicate that the decrease observed in the CTOD values can be related to the coarsening of the microstructure near the fusion boundary and also to the increase of the volume fraction of grain boundary ferrite and ferrite side plates. Cane et al (12) and others (13) associate a decrease of the notch toughness with an increase in the volume of upper bainite. In the present study, however, it was observed that a decrease of upper bainite was accompanied by an increase of the fraction volume of grain boundary ferrite and ferrite sides plates which are generally considered detrimental to the notch toughness as reported by Dolby (14) for the HAZ of C-Mn steels despite a fall in hardness of the coarse grained zone of the HAZ.

Very few studies are published, to the author's knowledge, on quantitative metallography in the HAZ so further studies are necessary to confirm the trend observed in the present work.

Although there is a marked decrease of the notch toughness with increase in cooling time the values obtained even for the highest heat input used seem to indicate that the degradation of the fusion boundary notch toughness of the steel tested is not as severe as reported in a presentation by Wintermark (15) for other types of steels, mainly low carbon (< 0.12% C) microalloyed high strength steels. It is intended to pursue the present research work to study other types of steels in order evaluate the composition effect in the fusion boundary notch toughness.

CONCLUSIONS

The increase of the cooling time led to an increase of the austenite grain size and coarsening of the microstructure in the fusion boundary of the HAZ.

An increase of the volume fraction of grain boundary ferrite and ferrite side plates and a decrease of upper bainite with the increase of cooling time (Δt 8/5) was observed.

A correlation was found between the CTOD notch toughness and microstructure. A decrease of notch toughness was found when the cooling time increased. However even for the highest cooling time tested the CTOD notch toughness values obtained can be considered reasonable.

Charpy V testing was not considered to be apropriate to discriminate the influence of cooling time in the notch toughness of the HAZ fusion boundary.

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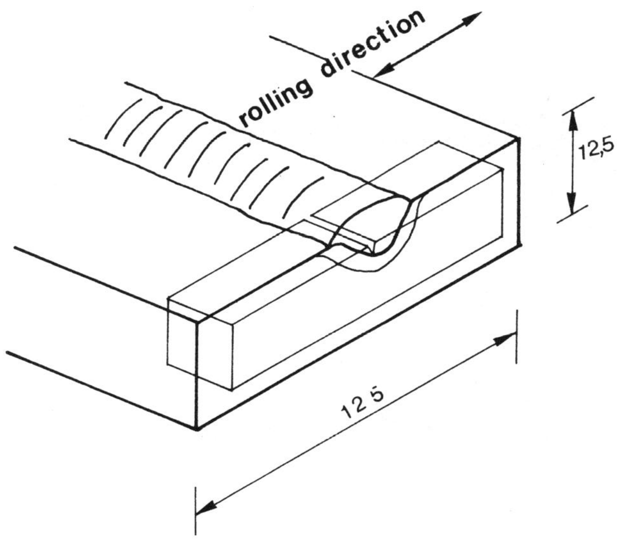

Figure 1 Location of specimen and orientation of the notch

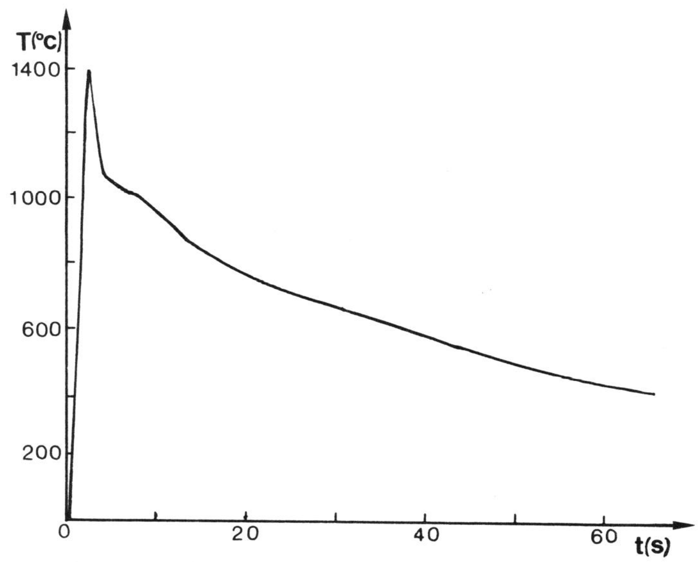

Figure 2 Typical HAZ thermal cycle (1.9 KJ/mm heat input)

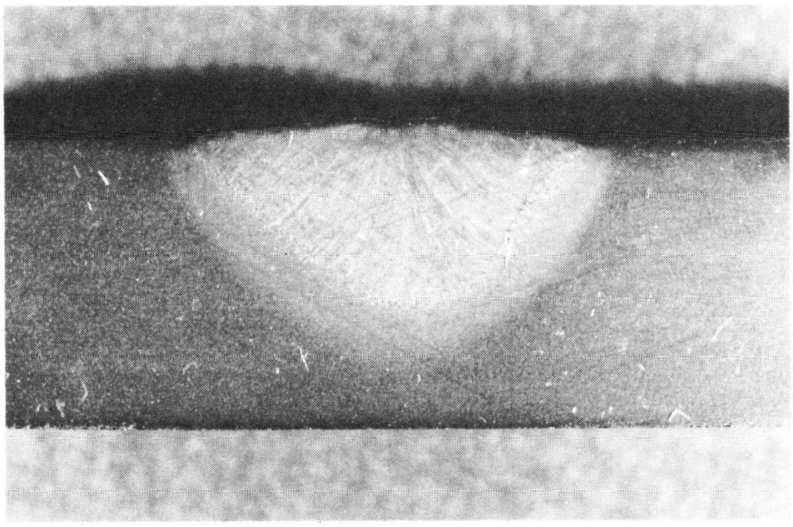

Figure 3 Macrograph of specimen produced with a heat input of 2.2 KJ/mm

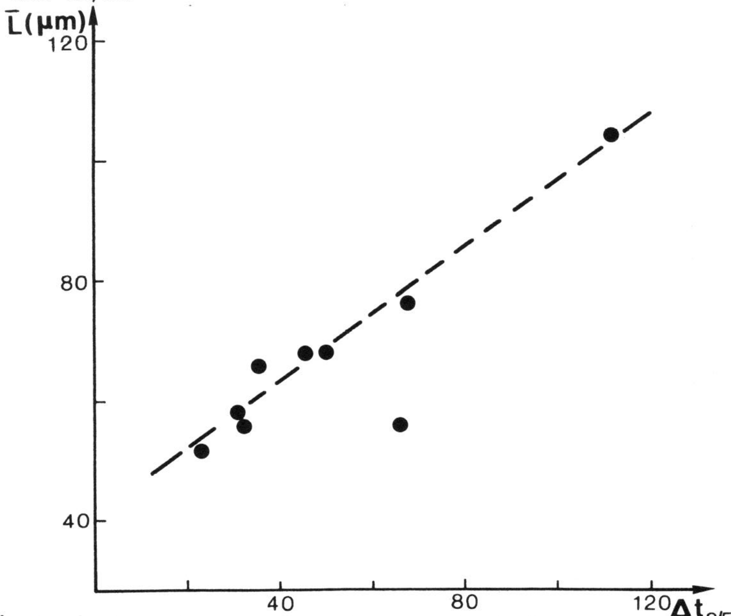

Figure 4 Correlation of grain size in fusion boundary of the HAZ and the cooling time

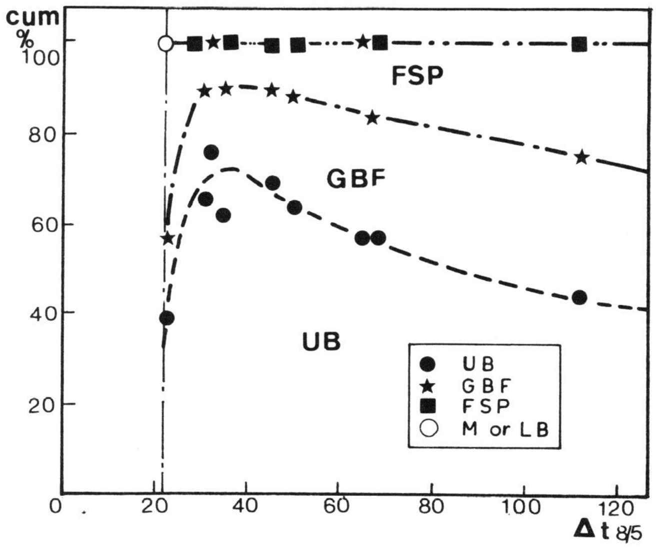

Figure 5 Constituent volume fraction

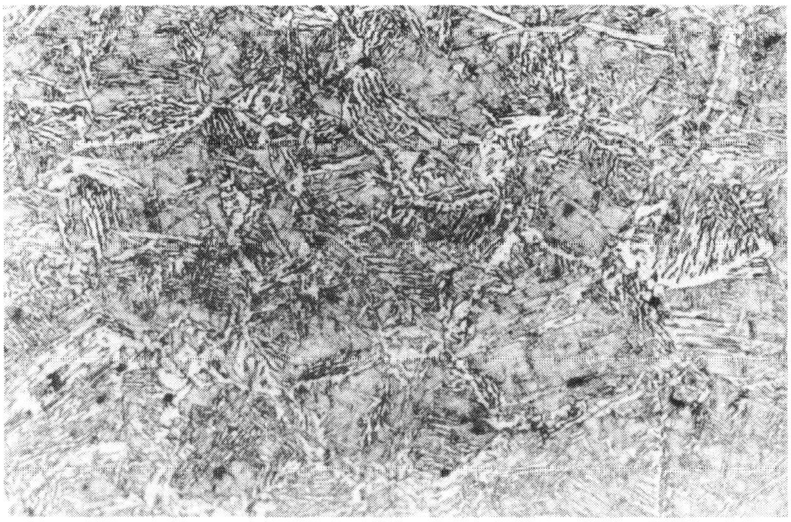

Figure 6 Typical microstructure obtained for a cooling time of Δt 8/5 = 23 s

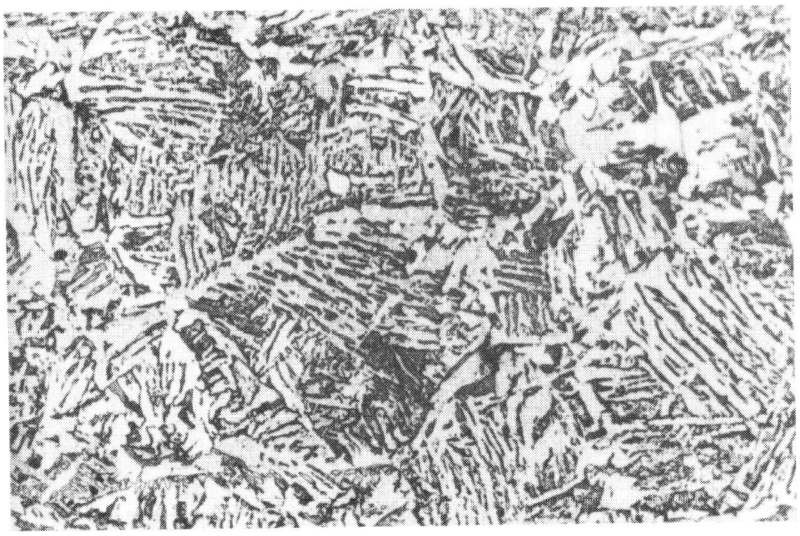

Figure 7 Typical microstructure obtained for a cooling time of Δt 8/5 = 112 s

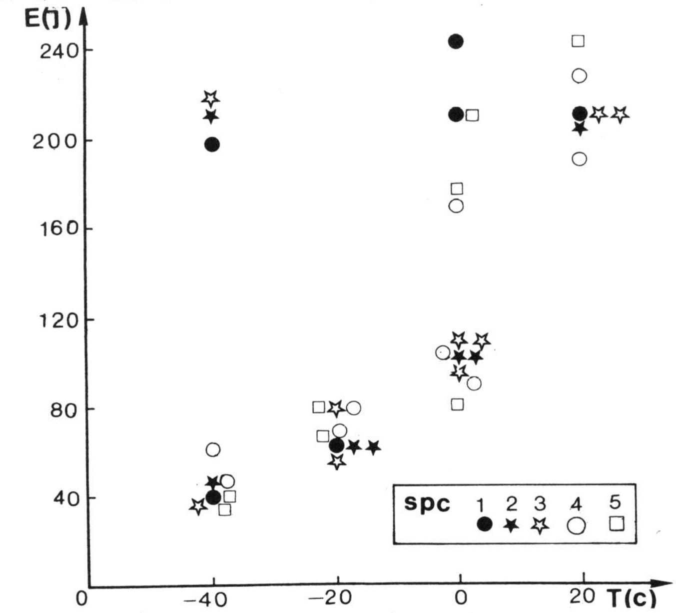

Figure 8 Notch toughness properties as measured by the Charpy V testing

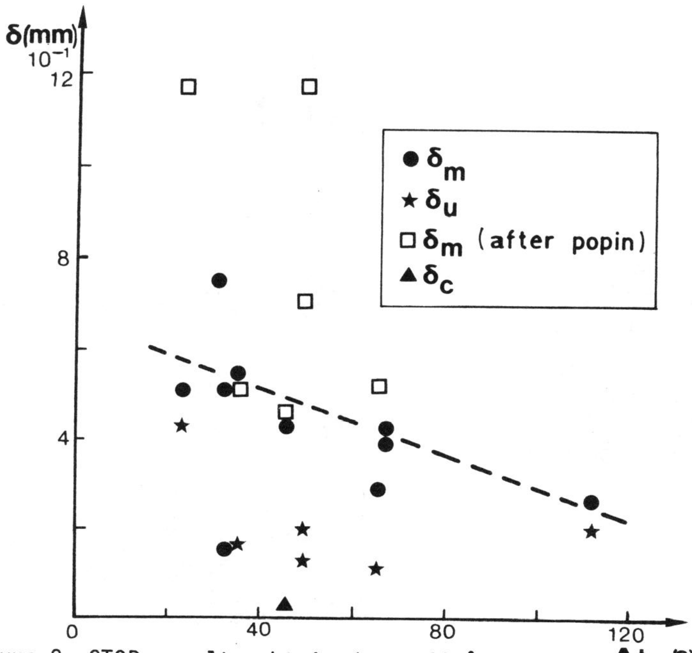

Figure 9 CTOD results obtained at -10 °C

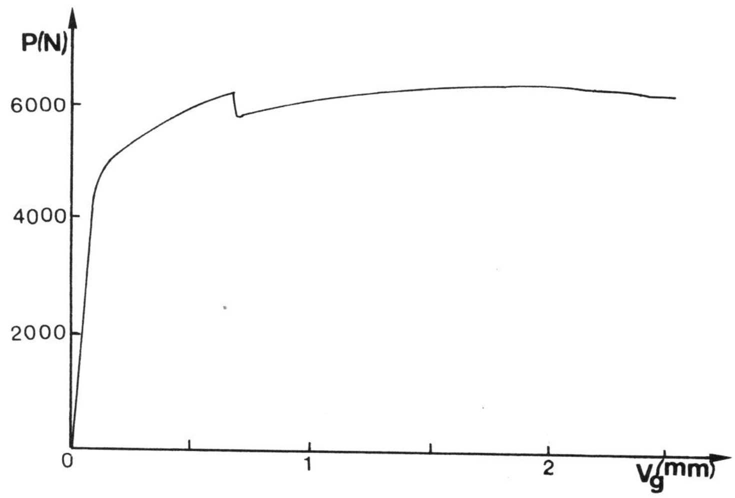

Figure 10 Specimen displaying pop-in behaviour

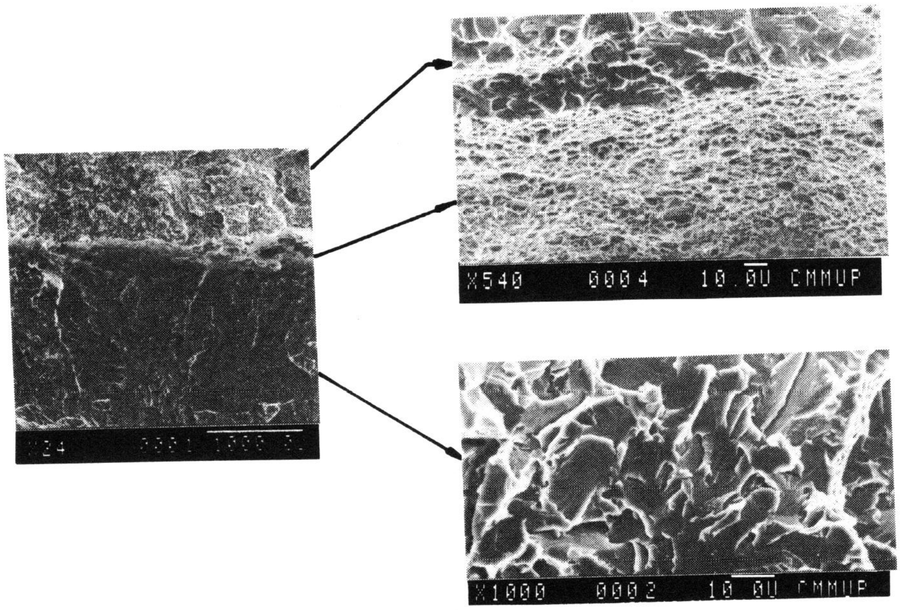

Figure 11 Crack arrest observed in Charpy V specimen 1