CTOD TESTING OF WELD METALS: THE IMPORTANCE OF POP-INS

J.E.C.SALDANHA PERES*
J.H.Rogerson**

The CTOD test is used to assess fracture initiation properties and its value on weld metal is dependent not only on the factors which affect the results on plate material, but also on welding procedure and on the specimen geometry. Furthermore several difficulties have been observed when testing weld metals. A major difficulty is related with the assessment of the significance of pop-ins, which are frequently observed in tests on weld metal. This paper describes an investigation into CTOD testing of weld metals in C-Mn steels partly to see to what extent pop-ins should be considered as significant events and generally to consider the uncertainties in the interpretation of CTOD tests of weld metal.

INTRODUCTION

It is well known that if there is a risk of a welded structure suffering from fracture, such a failure will most probably arise from a crack initiated by a weld defect. Hence the need to use fracture mechanics methods which aim to establish a relationship between the applied stress, the fracture toughness of the weldment and the existence of weld defects. With the use of such a relationship it is possible to determine the maximum allowable defect size for a given toughness level or the minimum required toughness level for a given defect size. The measurement of the toughness of weldments, and particularly weld metals, is not straight-forward but a frequently used small scale test for ductile materials (which includes most steels used in welded constructions) is the CTOD test carried out according to BS 5762:1979 (1).

The CTOD is used to assess fracture initiation properties and its value on the plate material is affected by several factors, Harrison(2), such as strain rate temperature, thickness, type of testing machine and testing technique.

The CTOD test was designed for measuring the toughness of steel plate and the standard gives some guidance to limit the variations caused by such factors by requiring the testing of full thickness specimens at

---

*Assistant lecturer, University of Minho, 4800 Guimarães, Portugal
**Senior lecturer, Cranfield Institute of Technology, Cranfield, Bedford MK 43 OAL, England

the temperature of interest within certain limits of strain rate. Much more variation occurs when testing weld metals as the fracture toughness is dependent not only on those factors, Pisarski et al(3), Marshall(4), but also on the welding procedure (e.g. welding process, consumables, preheat, interpass temperature, heat input, welding position and welding technique, joint configuration, degree of restraint, post weld heat treatment, root treatment and level of hydrogen present), and on the specimen geometry. Furthermore, several difficulties have been observed when testing weld metals. It is difficult to obtain an acceptable crack shape, Leggatt et al(5), due to the presence of residual stresses and to the inhomogeneity of weld metals. A major difficulty in interpreting the CTOD test results is related to the occurrence of pop-ins which are transient instabilities on the load/clip gauge displacement curves, usually associated with arrested short brittle cracks. These pop-ins are frequently observed, Dawes et al(6), in tests on weldmetal due to its inhomogeneity and correspond to the lower values of toughness obtained. Their significance in the assessment of structural behaviour has been questioned by several authors, Pisarski(7), Kamath(8), Kamath et al(9), since their occurrence depends not only on the material toughness but also on the testing techniques. These factors make it sometimes difficult to assign correct toughness values to weldmetals.

This paper describes an investigation into CTOD testing of weldmetals in carbon-manganese steels partly to see to what extent pop-ins should be considered as significant events and define the fracture properties of the weld and partly to what extent they are merely characteristics of the test procedure which is not primarily designed for testing weldmetals and generally to consider the uncertainties in the interpretation of CTOD testing of weldmetals.

EXPERIMENTAL PROCEDURE

Materials

Welds were made on 25mm thick C-Mn steel plate to BS 4360 Grade 50D (see Table 1 for composition) with 4mm diameter manual metal arc electrodes to AWS E7016.

Welding Procedures

Vertical up welds were made in an equal Double-V 60° included angle preparation on pairs of plates 900 x 600mm. The details of the procedure are given in Table 2, and the geometry of the joint is shown in Figure 1. Two of these welded panels were 'repaired' over a length of 100mm at their mid section, using the same welding procedure. Details of the repair groove are given in Figure 2.

Fracture Testing

The reinforcement was taken off and full thickness specimens with a notch perpendicular to the plate surface were used, manufactured and tested in accordance with BS 5762 (1). Most specimens contained some degree of distortion.

To ensure satisfactory fatigue crack shape, Dawes (10), the uncracked specimens were plastically strained in compression at strains between 0.7% and 1%. The fatigue cracks were grown at a stress ratio of 0.1 with a maximum stress intensity factor less than 800 $N/mm^{-3/2}$. The crack growth was carefully monitored and allowed to grow to a length of 25mm (an a/W ratio of 0.5). Specimens were fractured in a 50 ton Universal Testing Machine at a temperature of -10ºC. Following testing the specimens were broken open after being cooled in liquid nitrogen and all the fatigue cracks (except one whose result was then discounted) were found to be regular and within the limits allowed by the standard.

CTOD Results

CTOD results from the three welded testplates are given in Table 3. Various types of traces were obtained and the corresponding CTOD types were assigned and are also given in Table 3. A very small number of specimens (5 out of 35) failed at maximum load. A large number of specimens suffered pop-ins (18 out of 35) which were mainly of two types designated on this study by Type A and Type B (see Figures 3 and 4 for examples of load/clip gauge traces and associated fracture surfaces). With the Type A pop-ins there was no decrease in load the discontinuity on the trace was very small (17 to 58 μm in terms of clip gauge displacement) and the pop-ins (there were sometimes up to six on one specimen) always occurred near the linear range of the load/displacement curve. The Type B pop-in did cause a decrease in load and the discontinuity was larger. The occurrence of pop-ins Type A is not described in the BS 5762. It should be noted when considering Table 3 that some of the test specimens were purposely selected from areas where weld 'repairs' had been made. All but one of the specimens from the repair area gave values at the lower bound for the results, displaying pop-in Type A behaviour. As well as reporting the CTOD values strictly as defined in BS 5762, alternative estimates of CTOD were made. In the specimens where Type A pop-ins occurred, CTOD was recorded (Table 4) ignoring the first pop-in. Maximum load value of CTOD was also recorded (Table 5) when an increase in load occurred after the first instability (which gave the valid

CTOD reading). As can be seen, the ratio between these maximum load CTOD and the valid CTOD range from 2.2 to 20.9.

Fracture Examination

Visual examination of fracture surfaces was made after final separation of the specimens in liquid nitrogen. Typical fracture surfaces are shown in Figures 4, 5 and 6. In general the fatigue crack was of regular shape which was expected due to the precompression given. The existence of arrested short brittle cracks could also be seen on the fracture surfaces of most specimens which displayed pop-in behaviour (Figure 4).

Fracture initiated (except for the repaired weldmetals) in the mid thicknes of the specimen, i.e. in the root regions of the double-sided welds and sometimes the fracture was confined to a very restricted area. In welds which had been repaired the fracture initiation was not in the mid thickness and the fracture was confined to an even smaller region, see Figure 6. In a number of specimens there were small defects (porosity and solid inclusions) in the final fracture surface.

Hardness surveys across the weld, Table 6, showed that fracture initiated at the regions of highest hardness which was in the root in the as-welded specimens but away from the root in specimens which had been repaired.

DISCUSSION OF THE RESULTS

The results of the CTOD testing and the subsequent analysis of the fracture patterns clearly indicate that fracture initiated at, and was confined to, small areas at or near the root of the weld. Also, in many cases, small brittle cracks occurred which were arrested before final fracture, leading to pop-ins. Small weld defects were also observed on or near the fracture surface in some cases. At the same time the reported, valid CTOD results (according to BS 5762) are low compared to what might be expected from modern E7016 weldmetals and, when a repair weld had taken place, the reported toughness tended to be lower and with more arrested cracks.

The analysis of the fracture surfaces together with the results of the hardness survey is consistent with the existence of a narrow area of lower toughness at the root region leading, in some cases, to the initiation of brittle cracks which were subsequently arrested when growing to areas of higher toughness either as a result(9) of such higher toughness or as a result of the change in crack front shape reducing the stress intensity factor or even as a result of insufficient elastic stored

energy within the testpiece/machine system.

It has been well established Clark et al (11) Robinson(12) that there is frequently a change in weldmetal toughness through the cross-section of double-sided welds in C-Mn steels. In the case of MMA welds the thoughness in the root is normally lower than in the subsurface regions. This is a function of the welding procedure (12) and is attributed either to dynamic strain ageing or to dilution effects occurring at the root or even to the presence of residual stresses. The evidence of the hardness measurements indicates, in the case of the welds currently studied, that there is a microstructural or compositional variation through the thickness. The fracture is confined to the high hardness (assumed low toughness) regions in or near the mid section. In fact there is some evidence Dawson et al (13) Parlene et al (14) that the use of full weave techniques and/or of a small degree of restraint as in the present experiment leads to a reduction in the root toughness. Therefore, it seems that the CTOD result in an inhomogeneous material reflects the toughness of the least tough region, particularly if it is near the area of higher constraint.

The residual stress effect is not likely to be significant because of the precompression of the specimens (5) and the evidence of the shape of the crack fronts.

The significance of weld defects at or near the fracture is not clear. Certainly they existed in some cases and, on a microscale, we could expect that they might affect the shape of the load/displacement curve via their effect on the compliance and might be the cause of pop-ins.

It was not possible to match individual defects with particular pop-ins, so their effect is unknown but merits further study.

The fact that the fracture in these weldments was restricted to a particular region, presumably as a result of composition or microstructural factors, means that the importance of welding process and procedure is very great as it determines the pattern of the metallurgical inhomogeneity. It also emphasises that the preferred geometry specimen as used here (through thickness notch with W = 2B) which samples the whole range of weldmetal microstructure is more conservative than the subsidiary geometry specimen as the lowest toughness region is automatically sampled. Furthermore the preferred geometry has a higher degree of constraint which is over emphasised by the joint geometry used (double-V) due to the coincidence of the area of presumed lower toughness and the area of higher constraint (mid centre of the specimen).

The occurrence of the many pop-ins could therefore be explained in that they are a 'consequence of the presence of small, low toughness regions in the weldment at the area of higher constraint) which result in brittle, arrested cracks. The detection of a pop-ins, and its size, in a given circumstance is a function of the type of test machine which governs the dynamic response of the specimens and testing machine and of the response of the load/displacement recording system. There is certainly evidence in the literature (8),(9) that pop-in behaviour is affected by such factors and that when extra energy is available in the testing systems pop-ins become more extensive and in some cases complete failure occurs. It may be, therefore, that the distinction between Type A and Type B made in this series of tests would be different under a different testing arrangement (e.g.use of softer or load control machines instead of the displacement control testing machine used here).

Implications for the CTOD Testing of Weld Metals

It is clear from the foregoing discussion that the interpretation of the results of CTOD testing of weld metal is subject to some uncertainty which means that for prudence a conservative assessment must be made of weld metal fracture properties. The important implications can be summarised as follows:

The fact that the CTOD is strongly dependent upon the welding procedure and specimen geometry used, leads to the present practice of performing the tests on weldments representative of the worst conditions that are likely to occur on a given structure, using the specimen geometry which gives lower toughness results. This fact together with the use of the CTOD design curve which has been found highly conservative BURDEKIN (15) introduces an unknown degree of conservatism on the assessment of structures and makes difficult the attainment of the specified levels of toughness required in some design and manufacturing specifications.

The problem involved with the occurrence of pop-ins is to determine whether this crack arrest would occur in an actual structure or not. The usual argument is that the stored energy available in a structure is considerably larger than that existing on CTOD specimens. However pop-ins have been observed (9) even in large scale tests. It is then reasonable to suppose that some pop-ins may be ignored as they are not significant events, but the definition of rules to determine which to ignore is not yet feasible. The importance of the subject is very evident since, for example, the results presented here show that the CTOD ratio at final fracture to CTOD at pop-in varied from 2 to 20.

CONCLUSIONS

To be used for welding procedure qualification the CTOD testing must be improved particularly on those aspects related to the establishment of welding procedures for test plates, the choice of specimen geometry, the interpretation of discontinuities occuring on the load versus clip gauge displacement, the preparation of specimens and the presence of weld defects on the CTOD specimens. More knowledge is required on the significance of these variables.

The toughness of the weld metal as measured by the current CTOD test is significantly sensitive to details of the welding procedure and testing technique. This is mainly due to three factors. Firstly weld metal is relatively inhomogeneous in terms of composition and microstructure compared with steel plate. Secondly the welding operation introduces variables such as residual stresses and weld defects and thirdly the precise welding procedure causes variation on the toughness of the weld metal through the thickness affecting the choice of the specimen geometry and the importance of the testing technique, i.e. the complexity and sensitivity of the system.

Because the CTOD result is dependent on the toughness of the material sampled by the notch tip, the specimen geometry and notch location are particularly important for tests of weld metals. The arbitrary use of the two different geometries allowed by the standard can lead to completely different results,the lowest ones being more likely with the preferred geometry.

The occurrence of pop-ins is associated with the lowest CTOD values obtained being one of the major causes of the large scatter observed on CTOD tests.

The study of the post pop-in behaviour revealed that most of the specimens had higher resistance to fracture than that displayed by the pop-in, with the ratio CTOD at final fracture to CTOD at pop-in varying from 2 to 20. The scatter reduces significantly for the CTOD results at final fracture. More effort should be expanded in assessing the significance of pop-ins as critical events. In order to reduce the differences in CTOD results obtained by different laboratories, more precise requirements for testing machines and sensitivity of displacement measurements should be established.

Finally, the preparation of specimens from welded plates can lead to the use of distorted specimens and specimens which contain weld defects in the fracture path. There is no data on the effect upon the CTOD results that the presence of such discontibuities and weld defects can have. More effort should be expended to determine their influence and to establish limits for those defects on test panels.

ACKNOWLEDGEMENTS

One of the authors (J.E.C.Saldanha Peres) wishes to acknowledge the financial support from INVOTAN which enabled him to study at Cranfield Institute of Technology where this work was undertaken

LIST OF REFERENCES

1. BS 5762: 1979,'Methods for Crack Opening Displacement (COD) Testing', (British Standards Institution,London 1979).

2. Harrison, J.D. 'The State-Of-The-Art In Crack Tip Opening Displacement (CTOD) Testing and Analysis'.Metal Construction, 12,(1980) no.9,10,11.

3. Pisarski,H.G., and Dawes,M.G. 'Measurement of Crack Opening Displacement in Weldments with Particular Reference to Offshore Structures', (Welding Institute Report no.111/1980, London 1980).

4. Marshall, V.G. 'Procedural Requirements for Welded Joints in Offshore Structures-a Question of Validity', Metal Construction, 14 (1982), 528.

5. Leggatt, R.H., and Kamath, M.S. 'Residual Stresses in 25mm Thick Weld Metal COD Specimens in the As-Welded and Locally Compressed States', (Welding Institute Report 7713.01/81,London,1981)

6. Dawes, M.G.,Pisarski,H.G.,Towers,O.L., and Williams,S. 'Fracture Mechanics Measurements of Toughness in Welded Joints'. (Conference on Fracture Mechanics Toughness Testing -methods, interpretation and application, London,1982, Paper 33)

7. Pisarski,H.G. 'Influence of Thickness on Crack Opening Displacement (COD) and J Values',(Welding Institute report 90/1979, London 1979)

8. Kamath, M.S. 'Some Preliminary Findings on the Significance of Pop-ins in Fracture Toughness Testing', (Conference on Steels in Marine Structures Paris 1981)

9. Kamath, M.S. and Gittos, M.F. 'The Incidence of Pop-ins in Fracture Toughness Testing',The Welding Institute Research Bulletin, London April 1970, 117

10. Dawes, M.G. 'Contemporary Measurements of Weld Metal Fracture Toughness'. Welding Journal, 55 (1976) 1052

11. Clark, A., George, M.J., and Kirkwood,P.R. 'Welding in Offshore Structures',(The Welding Institute, 1974)

12. Robinson, J.L. 'Factors Controlling Root Run Toughness in Multipass MMA Welds in C-Mn Steels'. Welding Research International, 8, (1978) 425

13. Dawson, G.H., and Judson, P. 'Procedural Guidelines for the Achievement of Tough Welded Joints in Structural Steel for Offshore Applications', (2nd International Conference on Offshore Welded Structures, The Welding Institute, London 1982)

14. Parlene,A.J.A, and Leggatt, R.H. 'The Dependence of CTOD on the Level of Test Panel Restraint: Preliminary Report', (Welding Institute Report 7713.02/82,London 1982)

15. Burdekin, F.M. 'The PD 6493 Approach to Significance of Defects' (Fitness for Purpose Conference, Welding Institute, London 1981, Paper 37)

TABLE 1 (a)- Chemical compositions of parent metal (P), weld metal (AW), repair weld metal (R) and double-repair weld metal (RR). Weight %

Specimen	C	Si	Mn	P	S	Cr	Ni	Al	Mo	Co	Cu	Nb	Sn	Ti	B
P	0.17	0.29	1.32	0.016	0.022	0.07	0.03	0.04	0.01	0.005	0.04	0.027	0.008	0.004	0.0002
AW	0.07	0.41	1.45	0.012	0.005	0.03	0.02	0.02	<0.01	0.006	0.04	0.002	0.004	0.028	0.0002
R	0.07	0.43	1.48	0.011	0.004	0.03	0.03	0.02	<0.01	0.007	0.04	0.002	0.004	0.028	0.0002
RR	0.08	0.44	1.60	0.012	0.005	0.02	0.03	0.01	0.01	0.007	0.04	<0.002	0.004	0.031	0.0003

$V < 0.01$ $W < 0.02$

PARENT PLATE has a C.E. = 0.41, where $C.E. = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Cu + Ni}{15}$

TABLE 1 (b) - Tensile properties of weld metal (mean of two tests)

ULTIMATE TENSILE STRENGTH	579 N/mm^2
YIELD STRESS	462 N/mm^2
ELONGATION AT RUPTURE	29.3 %
REDUCTION OF AREA	71 %

TABLE 2. Welding procedure for weld metal tests

Base material:	BS4360 50D - 6 plates (900 x 600 x 25)
Edge Preparations:	Equal double-V, 60° included angle - flame cut.
Root gap:	3 mm.
Root face:	2 mm.
Welding process:	Manual metal arc welding (MMA)
Consumables:	AWS E7016 (BS639 E5156 B24 H) 4 mm diameter. BOC Ferex 7016, batch number 132050.
Welding position:	Vertical up
Power supply:	AC
Preheat:	Not required
Interpass temperature:	Maximum 250°C
Root treatment:	Ground until sound metal after completion of the first side.
Welding technique:	Multipass. Maximum run per electrode of 150 mm. Plates restrained during welding by clamping. No restrictions on weave. Mean heat input of 2.3KJ/mm.
Post weld heat treatment:	Not required.
M.M.A. electrode drying:	Dry 1 hour at 250°C and store at 150°C until use.
Run-on and run-off plates:	Use 50 mm length plate with the same groove geometry.

Table 3: CTOD Values for Weld Metal (E7016) at -10°C (B=25mm; W=50mm)

Specimen No. (2)	a/w	V_p (mm)	P_c (N)	P_{max} (N)	CTOD (1) (mm)	Type
AW1	0.524	0.086	37770	44450	0.051^{i}	δ_c
AW2	0.519	>0.143	43450	51820	0.077	
AW3	0.523	0.443	49260	49260	0.163	δ_m
AW4	0.534	0.079	33520	43930	0.044^{ii}	δ_c
AW5	0.525	0.108	40860	-	0.063^{i}	δ_c
AW6	0.527	0.088	38670	-	0.053^{i}	δ_c
AW7	0.525	0.188	44650	44650	0.089	δ_u
AW8	0.526	0.067	37210	47080	0.046^{i}	δ_c
AW9	0.533	0.113	38800	45050	0.061^{i}	δ_c
AW10	0.517	0.293	48730	48730	0.123	δ_u
AW12	0.514	0.256	48720	48720	0.112	δ_u

(1) The CTOD Values Marked With 'i' Correspond to Pop-ins Type B.
The CTOD Values Marked With 'ii' Correspond to Pop-ins Type A.

(2) The Specimens Marked With '*' are from a Repaired Area and those Marked with '**' are from a Double Repaired Area of the Test Panel

Specimen No (2)	a/w	V_p (mm)	P_c (N)	P_{max} (N)	CTOD (1) (mm)	Type
R1	0.514	0.975	56410	56410	0.316	δ_m
R2	0.525	0.025	31480	47640	0.027^{ii}	δ_c
R3	0.521	0.083	36870	47640	0.048^{i}	δ_c
R4	0.523	0.054	32970	41660	0.036^{ii}	δ_c
R5 *	0.523	0.056	34110	48040	0.033^{ii}	δ_c
R6 *	0.528	0.042	26340	45840	0.024^{ii}	δ_c
R7 *	0.526	0.075	30210	44650	0.038^{ii}	δ_c
R8	0.521	0.054	30740	51430	0.033^{ii}	δ_c
R9	0.529	0.288	47540	47540	0.120	δ_u
R10	0.526	0.135	42030	45050	0.070	δ_u
R11	0.525	0.275	48240	48240	0.117	δ_u
R12	0.535	1.188	52860	52860	0.355	δ_m

Table 3 - Continued.

Table 3 - Continued.

(2) Specimen No.	a/w	V_p (mm)	P_c (N)	P_{max} (N)	CTOD (1) (mm)	Type
RR1	0.521	0.117	37010	45840	0.057^{i}	δ_c
RR2	0.524	0.058	31490	48040	0.035^{ii}	δ_c
RR3	0.525	0.113	38350	47730	0.059^{i}	δ_c
RR4	0.524	0.348	48930	48930	0.138	δ_m
RR5 **	0.530	0.046	29370	46740	0.030^{ii}	δ_c
RR6 **	0.519	0.033	22600	50030	0.019^{ii}	δ_c
RR7 **	0.520	0.279	48830	48830	0.116	δ_u
RR8	0.524	0.367	48040	48040	0.136	δ_u
RR9	0.524	0.185	43350	43350	0.088	δ_u
RR10	0.513	0.394	48930	48930	0.152	δ_m
RR11	0.533	0.154	42360	42360	0.077	δ_u
RR12	0.521	0.137	41000	41660	0.069	δ_u

Table 4: Values of CTOD Corresponding to the Specimens which Displayed Pop-in of Type A if the First Pop-ins were Ignored (The Discontinuities on the Trace Corresponding to the Clip Gauge Displacement at Pop-ins were Discounted from the Value of V_p)

Specimen No.	a/w	V_p ' (mm)	Discontinuity at Pop-in (mm)	P' (N)	CTOD (1) (mm)	Type
AW4	0.534	0.258	0.033	4134	0.1017^{i}	δ_u
R2	0.525	0.094	0.021	3767	0.0529^{ii}	δ_c
R4	0.523	0.267	0.058	4156	0.0901	δ_u
R5	0.523	0.142	0.025	4043	0.0690^{ii}	δ_c
R6	0.528	0.121	0.021	3642	0.0552^{ii}	δ_c
R7	0.526	0.367	0.046	4445	0.1335^{i}	δ_u
R8	0.521	0.983	0.025	5143	0.3056	δ_m
RR2	0.524	0.650	0.050	4804	0.2124	δ_m
RR5	0.530	0.213	0.050	3899	0.0852^{ii}	δ_c
RR6	0.519	0.117	0.017	3484	0.0543^{ii}	δ_c

(1) The CTOD Values Marked with 'i' Correspond to a New Pop-in Type B. Those Marked with 'ii' Correspond to a New Pop-in Type A.

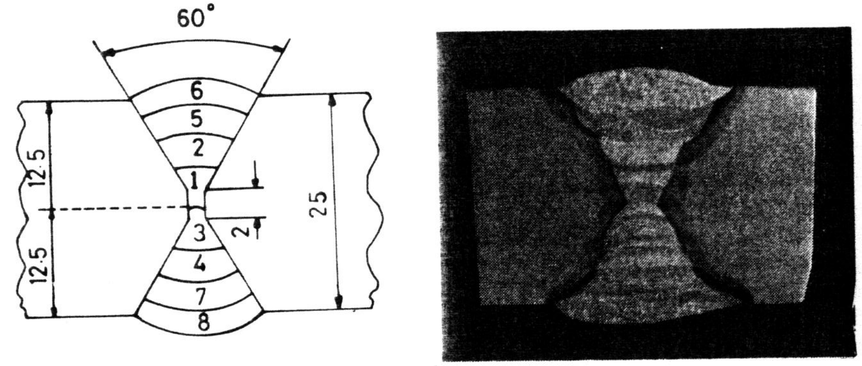
Table 5: Values of CTOD At Maximum Load (δ max) For Specimens Which Displayed Pop-ins

Specimen No.	No. off pop-ins	P_{max} (1)	$V_{P_{max}}$ (1)	δ_{max} (1)	δ	δ_{max}/δ
AW1	1	44450	0.613	0.197	0.051	3.9
AW4	2	43930	1.225	0.347	0.044	7.9
AW8	1	47080	0.963	0.290	0.046	6.3
AW9	1	45050	0.942	0.278	0.061	4.6
R2	2	47640	0.347	0.134	0.027	5.0
R3	2	47640	0.275	0.116	0.048	2.4
R4	1	41660	0.267	0.103	0.036	2.9
R5	4	48040	1.025	0.308	0.038	8.1
R6	6	45840	0.816	0.250	0.024	10.41
R7	1	44650	0.317	0.121	0.038	3.2
R8	1	51430	0.958	0.300	0.033	9.1
R10	1	45050	0.964	0.286	0.070	4.1
RR1	1	45840	0.658	0.211	0.057	3.7
RR2	1	48040	0.592	0.198	0.035	5.7
RR3	1	46730	1.533	0.434	0.059	7.4
RR5	2	46740	0.675	0.215	0.030	7.2
RR6	5	50030	1.342	0.397	0.019	20.9
RR12	2	41660	0.446	0.150	0.069	2.2

Table 6 - Hardness Data From A Survey Over The Weld Metal in the Through Thickness Direction.

Depth below plate surface (mm)	Hardness Hv_{10}		
	As-weld Cross Section	Repair Weld Cross Section (1)	Double Repair Weld Cross Section (1)
1.2	234	218*	234**
2.4	222	213*	229**
3.6	204	179*	223**
4.8	194	207*	202**
6.0	210	207*	209**
7.2	230	195*	202.5*
8.4	225	198	229*
9.6	228	204	213
10.8	253	241	239
12.0	248	258	237
13.2	240	281	244
14.4	234	255	246
15.6	245	251	244
16.8	202	233	219
18.0	197	201	192
19.2	228	175	190
20.4	213	202	188
21.6	220	206	197
22.8	225	217	220
24.0	231	225	208

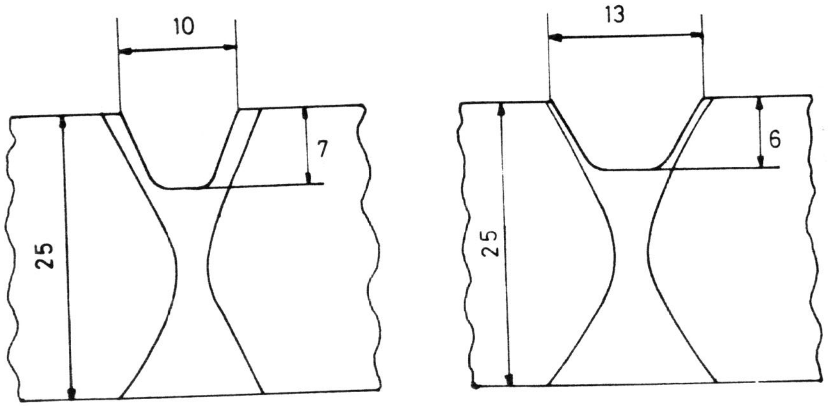
(1) The Values Marked With '*' Correspond to Hardness Values Obtained Over The Repair Weld Metal. Those Marked With '**' Correspond To Hardness Taken Over The Double Repair Weld Metal.



a) Joint Preparation and
Run Sequence.

b) Macrograph of the Welded
Joint

Figure 1. Details of Welded Joint Geometry and Run Sequence

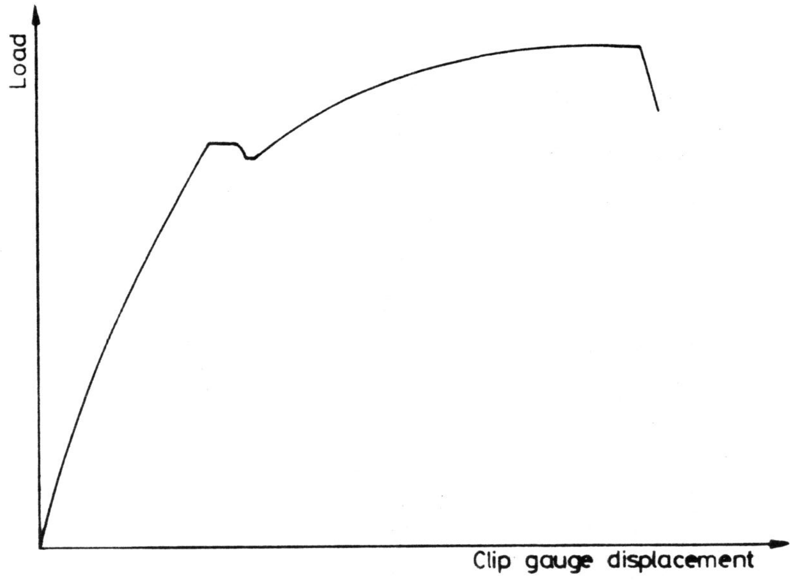


a) Repair

b) Double repair

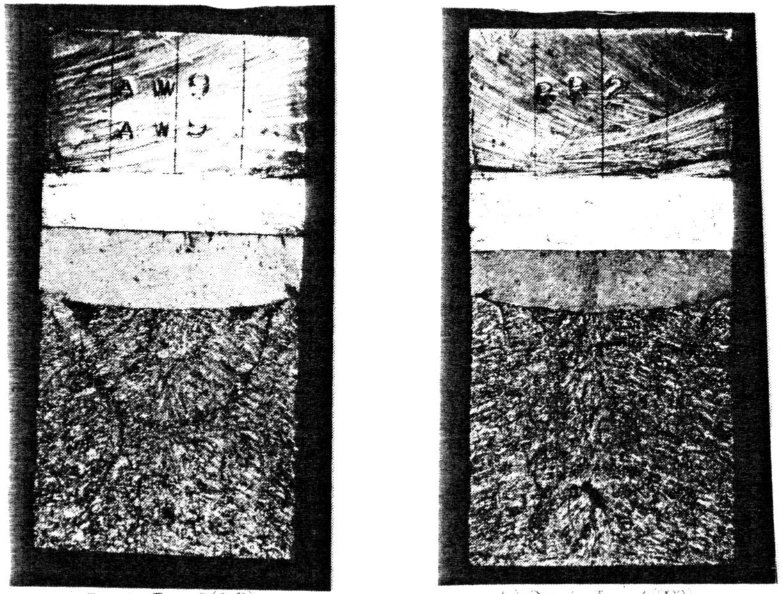
Fig. 2 Typical groove cross section used on the repair and the double repair operation.

a) Various pop-ins type A



b) Pop-in type B

Fig. 3 Types of pop-in more often observed



a) Pop-in Type B(AW9) b) Pop-in Type A(RR2)

Fig.4 - Fracture appearance of specimens exhibiting pop-ins.

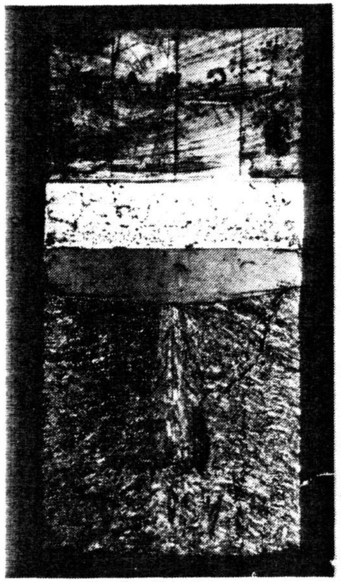
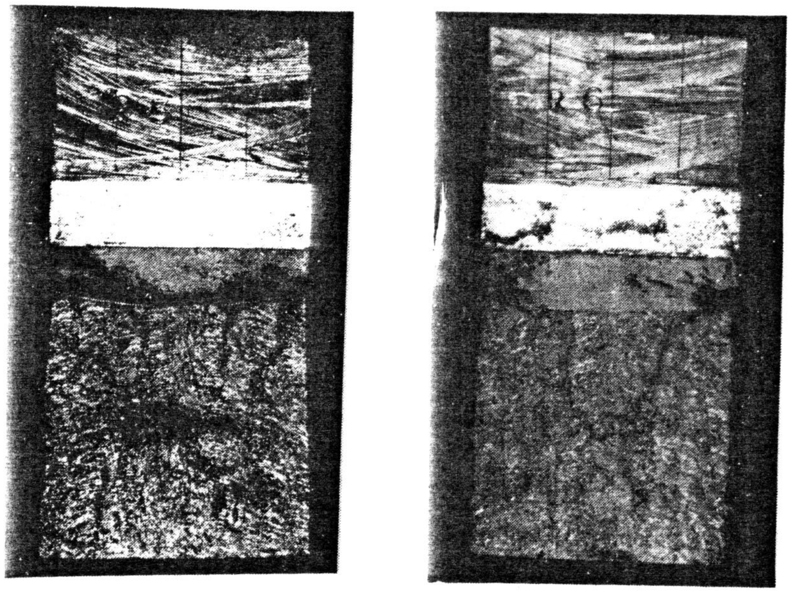
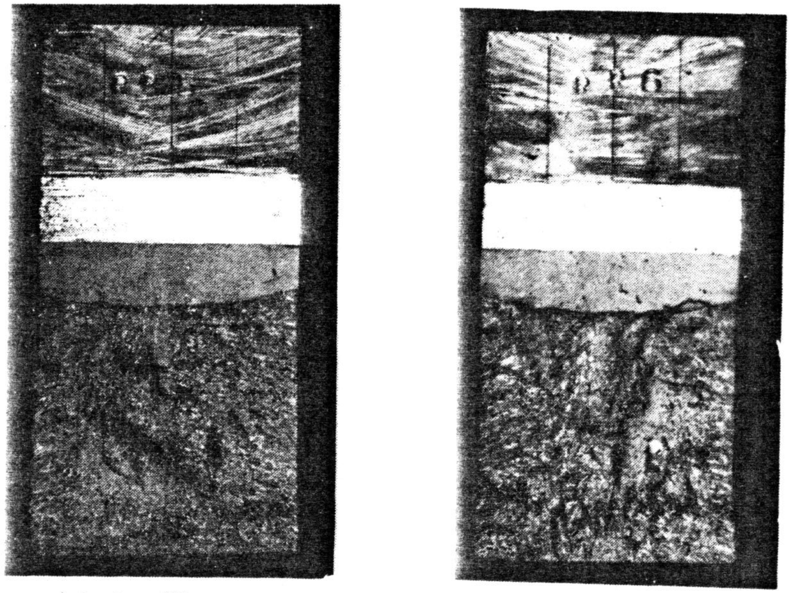


Fig.5 - Fracture appearance of a specimen which did not display pop-in (AW2)



c) Specimen R5 d) Specimen R6



e) Specimen RR5 f) Specimen RR6

Fig.6 - Fracture appearance of spec[illegible]