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BRITTLE WELD SELECTION FOR OPTIMUM PERFORMANCE IN CRACK ARREST TOUGHNESS TESTS

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ABSTRACT

In crack arrest tests fast running cracks are usually initiated from either weld bead deposits or strain age embrittled notches. In previously reported work, tests were carried out on 15 mm thick 350WT grade steel plate using full thickness compact crack arrest (CCA) specimens with strain aged chevron notches. Crack arrest toughness (K_v) varied between 95 to 155 MPa√m over the temperature range –40 to -15°C. The steel's NDTT was -40°C.

The results also indicated that for optimum performance the crack starter needed to have different degrees of embrittlement depending on the specimen size and/or test material toughness. For a successful test, the higher the material crack arrest toughness level the larger the required specimen size, and the higher the stored energy needed before crack initiation. As a result, in this case the crack starter material needs to be capable of delaying the triggering of the crack run event. Similarly, smaller specimens designed to determine lower toughness need a lower stored energy prior to crack initiation.

The suitability of several weld electrodes with different hardness and toughness levels has been assessed in terms of their ability to initiate running cracks at various temperatures.

RÉSUMÉ

Au cours d'essais d'arrêt de la fissuration, les criques à croissance rapide sont normalement amorcées par des dépôts de cordon de soudure ou par des entailles fragilisées par vieillissement artificiel. Lors d'études signalées précédemment, les essais étaient effectués à l'aide d'éprouvettes compactes et épaisses, découpées dans une plaque d'acier 350WY de 15 mm d'épaisseur, comportant des entailles en chevron vieillies artificiellement. La ténacité résiduelle (K_v) variait de 95 à 155 Mpa%m dans la plage de températures de -40 à -15 °C. La température de réduction de la ductilité à zéro était de -40 °C.

Les résultats indiquaient également que, pour atteindre la performance optimale, l'amorceur de fissuration doit présenter différents degrés de fragilisation selon la taille de l'éprouvette ou la ténacité du matériau d'essai. Pour que l'essai soit réussi, plus la ténacité résiduelle du matériau est élevée, plus la taille requise de l'éprouvette doit être grande et plus la quantité d'énergie stockée nécessaire avant l'amorçage de la fissuration doit être importante. En conséquence, le matériau amorçant la fissuration doit être capable, dans ce cas, de retarder le déclenchement du processus de fissuration. De même, dans le cas d'éprouvettes plus petites conçues pour déterminer une ténacité plus faible, il faut une quantité moindre d'énergie stockée avant l'amorçage de la fissuration.

Nous avons évalué dans quelle mesure plusieurs électrodes de soudage présentant différentes dureté et ténacité permettent d'amorcer, à diverses températures, la croissance de criques.

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Brittle Weld Selection for Optimum Performance in Crack Arrest Toughness Tests

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EXECUTIVE SUMMARY

There are two principal ways of avoiding brittle fracture in welded structures such as warship hulls. The first is to prevent crack initiation or unstable crack extension by ensuring adequate notch toughness and fatigue resistance in the steel plates and welds after assembly, and by minimizing the effect of sharp corners or other stress raisers. This requires high standards of quality control and workmanship during construction, although even then welds will contain regions of low toughness or small defects. Given a sketchy knowledge of typical operating loads and flaw sizes, it is also difficult to quantify the effect of stress concentrators and residual stresses. Very conservative assumptions about the applied stresses can lead to very pessimistic estimates of tolerable flaw size.

The second approach is to use materials capable of arresting running cracks. The "crack arrest toughness" must be high enough so that when a crack emerges from the region of high stress and/or low toughness where it was able to initiate, it can no longer propagate. This is a simple concept, but there are numerous difficulties in its application. Test techniques for measuring the crack arrest performance of relatively thick steels and welds have been developed, but they are difficult to use and very expensive. There is also uncertainty about the underlying theory of crack arrest. As a result crack arrest methodology has only been rigorously used for a few special applications on relatively thick materials under plane strain loading conditions. In recent years the availability of better instrumentation and more sophisticated structural analysis has increased the interest in crack arrest for a wider range of applications, including the relatively thin hulls of ships.

An ongoing project has assessed the suitability crack arrest test methods for ship construction materials. Previous DREA contract work measured the arrest toughness of 350WT steel and heat affected zone, and compared methods for initiating the running crack. This report describes a final effort to optimize crack starters, which is probably the most difficult requirement of the test method.

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1.0 INTRODUCTION

Previous work (1) was aimed at adapting ASTM test procedure E1221 to non-plane strain specimens. The resulting data provided some guidance in selecting appropriate brittle weld metal to initiate cracks within the specified crack mouth opening displacement (CMOD) limits at different levels of arrest toughness. Fig 1 indicates that as the arrest toughness to be measured increases, for example as a result of an increase in the test temperature, the crack starter toughness needs to be increased accordingly. In addition, the starter initiation toughness needs to be greater than the arrest toughness to be measured. It was thus concluded that different electrodes would have to be used for the measurement of crack arrest toughness at different temperatures.

Some success was achieved in a recent DREA funded project on this subject (2). Following ASTM Test Method E1221-96 guidelines, it was found that a brittle weld made from the electrode Foxdur 350 was successful in measuring high levels of arrest toughness using the appropriately sized CCA specimen. However, at lower arrest toughness values measured close to the Nil Ductility Transition Temperature (NDTT), Foxdur 500 was found to give a success rate of only 1 toughness estimate in three tests.

The objective of this investigation was to assess the suitability of selected weld electrodes for improving the success rate in measuring crack arrest toughness at a) test temperatures close to the NDTT where the toughness should be low, and b) at a temperature where the arrest toughness has some intermediate value.

2.0 MATERIAL

The test material used was the same 15 mm thick control rolled CSA G40.21 Grade 350 WT steel investigated in the earlier EDRD funded projects which has the composition shown in Table I (2,3). The measured crack arrest toughness in the L-T orientation, using various starter materials ranged from 121 to 172 MPa√m at -15°C (many successful tests) and 93 MPa√m at -30°C (specimen W = 175 mm, 1 valid test out of three). Smaller specimens (W=100 mm) tested at or below -40°C (NDTT), produced one valid result, 66 MPa√m, at -40°C.

3.0 DESIGN AND MANUFACTURE OF NON-PLANE STRAIN SPECIMENS

Specimen sizes were determined according to the procedure outlined by Crosley and Ripling (4). The test matrix for the present investigation is shown in Table II. For specimens of size W = 175 mm, with K_v = 122 MPa√m, so that the selected starter material would require an initiation toughness in excess of this value. It was anticipated that UTP DUR 400 weld bead would have lower initiation toughness, whereas, Foxdur 350 has been found to have a value greater than 150 MPa√m (Fig 1). Therefore it was expected that crack initiation would occur within the specified CMOD limits (4), resulting in sufficient driving force for this specimen size when using Foxdur 350. For the smaller specimen with K_v = 94 MPa√m, it was expected that UTP DUR 400 electrode would provide an acceptable level of initiation toughness.

Following (4) the in-plane specimen dimensions are shown in Fig 2 in terms of W. The loading hole diameter (D) was 31 mm. The slot geometry (L-T direction) was in accordance with ASTM E1221–96.

Brittle weld beads produced using the Foxdur 350 and UTP DUR 400 electrodes were also deposited following ASTM E1221-96, Appendix IX. In both cases, de-magnetization was employed. The EDM notch was placed in the weld bead using a 0.25 mm wire to a depth of 2 to 4 mm, resulting in an a_0/W ratio of 0.35. Rockwell hardness was measured on the in-plane surface on the starter weld bead of a few of the specimens. For Foxdur 350 and UTP DUR 400 welds the HRC values averaged 31± 2 and 42 ± 1, respectively. The weld deposit of UTP DUR thus has a lower hardness than the HRC 48 found for Foxdur 500.

4.0 TEST PROCEDURE AND RESULTS

4.1 Intermediate Specimens (W = 175 mm)

Tests were conducted in the temperature range –20 to -30°C measured at about 35 mm from the root of the EDM notch using a spot welded thermocouple. The temperature controller operated a solenoid that controlled the liquid nitrogen spray for cooling the specimen. Once the temperature has stabilized within ± 2°C of the set value, the test was commenced.

Loading was carried out in accordance with ASTM E1221-96. Up to 6 load cycles were employed. The increase in CMOD for the last (6th) cycle was made equal to the one before. This modification takes the final CMOD to slightly above the value recommended in the standard to ensure a valid result. The two CMOD limits suggested in (4) were also marked on the plot, and this reference indicates that a run-arrest event should occur within these limits for a successful test. The lower limit falls in between the first and the second unloading limits of the ASTM procedure. The upper limit falls between the 5th and 6th cycle limits.

a) Specimens with a Foxdur 350 brittle bead starter

In all of these specimens (1 thru 3), a run-arrest event occurred in the third cycle, above the lower CMOD limit suggested by Crosley and Ripling. The load drop was small, the largest (22%) being in the specimen tested at –30°C (the other two tests were performed at –25°C). The results indicate that the arrest toughness is higher than the anticipated value of

120 MPa√m. The calculated stress intensity at initiation (K_o) values for this specimen was 142 to 167 MPa√m and these values fall within the range of results presented in Fig 1.

b) Specimens with a UTP DUR 400 brittle bead starter

The first specimen was taken up to the limit of the 6th cycle without any audible event, and therefore the test was terminated. In-plane observation showed that the brittle bead had cracked from the EDM notch and arrested on entering the base metal. The second specimen (#5), tested at –20°C, produced an audible event clearly visible on the load - CMOD trace during the 1st loading cycle. The calculated stress intensity at initiation (K_o) value for this specimen was 102 MPa√m. The results indicate that UTP DUR 400 produces premature initiation with insufficient driving force for this size of specimen at this temperature.

4.2 Small Specimens (W = 100 mm)

Specimens with a UTP DUR 400 brittle bead starter

All of these tests (specimens 6 through 8) were conducted at -40°C. The procedure was as described above. After the first load cycle, because of a minute audible event, the specimen starter was examined. In-plane observations showed that the weld bead had a fine crack from the EDM notch. In the other two specimens similar events occurred with no clear indication from the load-CMOD trace of initiation during the first cycle. These specimens were loaded for the second cycle to see if a significant load drop occurred. Observations showed cracks in both, so no further loadings were carried out. These results confirm that the UTP DUR 400 weld bead produces premature crack initiation at –40°C for this specimen size.

4.3 Fracture Surface Observations

The specimens that had run-arrest events within the Crosley-Ripling CMOD limits, i.e. all three specimens with the Foxdur 350 weld starter, were broken open after heat tinting to expose the crack run. In all three the crack arrested immediately upon entering the base metal and hence had insufficient crack run to calculate arrest toughness. An example is presented in Fig 3.

4.4 Additional Testing

When taking crack extension measurements from the specimen displayed in Fig 3, it was noticed that the plate thickness was 16.4 mm. This was about 1 mm greater than the specimen thickness measured in previous work (2,3). The thickness of the other two specimens from this batch was also greater than 16 mm. All of the specimens tested in this phase of work were extracted from end of the plate, received at the start of the program to test the 15 mm (nominal) thickness 350 WT plate, with respect to the rolling direction.

The specimens were in the L-T orientation, so that the intended crack plane may have been as close as 110 mm from the end. It is known that controlled rolled plate can vary in mechanical properties due to edge effects, such as temperature differentials during thermo-mechanical processing. The difference in thickness could be an indication of this effect. A small piece of plate remained from the previous work with a thickness 15.6 mm, and it was decided to perform additional testing using this piece.

The largest specimen size that could be machined from the 15.6 mm thick plate was with W = 142 mm. The anticipated arrest toughness (K_v) at –30°C for this size is 110 MPa√m and is less than 120 MPa√m for specimen size W = 175 mm. As only two specimens could be machined from the left-over plate the third specimen was machined from the remainder of the 16.4 mm plate to complete a set of three. The starter weld bead was Foxdur 350. All three tests were conducted at –30°C.

In two specimens, a run-arrest event occurred in the fifth cycle, and in the third it was in the fourth cycle. In one test, the specimen with the larger thickness, the load drop was small, i.e. 18%, while the other two produced significant run-arrest events with load drop of ~ 50%. The calculated stress intensity at initiation (K_o) for this specimen was 163 to 185 MPa√m and these data also fall into the range of results presented in Fig 1. All three specimens were broken open at liquid nitrogen temperature. In the specimen with a load drop of 18%, the crack had stopped at the end of the brittle bead, (Fig 4a); in contrast, Fig 4b shows the crack run in one of the specimens that produced a larger load drop.

4.5 Calculation of Crack Arrest Toughness

For two specimens with crack runs, the arrest toughness was determined in accordance with ASTM E1221-96. In both these tests the ASTM validity requirements were met, except for (C), which is a condition to be met for plane strain and is not applicable for these full thickness tests. Finally, the plasticity correction factor employed by Crosely and Ripling (4) for full thickness specimens was applied to the crack arrest toughness (K_a) value obtained from the ASTM expression as described in the previous work (3), and the corrected value is reported as K_a* in Table III. Table IV gives the results from the other tests.

5.0 DISCUSSION

5.1 Comparison with Previous Results

The two specimens with plate thickness about 15.5 mm produced crack arrest toughness values of 95 and 93 MPa√m at –30°C. In the earlier work (3), which employed chevron notch crack starters and a single loading cycle, at this intermediate level of toughness the only valid value obtained from three tests was 93 MPa√m. Matching the brittle bead initiation toughness with the expected arrest toughness clearly improves the success rate of this test method. The thicker material at the end of the plate appears to have a higher arrest toughness than originally anticipated based on previous work. Table IV indicates that the arrest toughness may be greater than 120 MPa√m.

5.2 Suitability of UTP DUR 400 as a Crack Starter Brittle Weld

UTP DUR 400 was selected because the reported hardness of a weld bead layer on low carbon steel was HRC 40 compared to HRC 48 obtained for Foxdur 500. The measured hardness of the brittle starters was in agreement with these values. Five of the eight specimens in the planned test matrix (Table I) had this starter. While two of the five specimens were designed to determine the intermediate toughness level (at –25°C), the other three were for measuring the lower toughness at the NDTT. In all of these specimens crack initiation took place in the first cycle. In specimen #5, the event was clearly marked on the load-CMOD trace, but in the others there was no such indication. For test #5, therefore, the crack initiation stress intensity factor (K_0) was determined to be 102 MPa√m at –20°C. This is about the same initiation toughness as for Foxdur 500 (Fig 1).

5.3 Relation between (K_0) for the Crack Starter and Arrest Toughness.

This relationship was presented in Fig 1, and the current two results are included to cover the intermediate toughness level in Fig 5. The information in this figure is useful in selecting brittle weld bead types to for CCA testing in a range of crack arrest toughness levels.

6.0 CONCLUSIONS

The two objectives of this investigation were as follows:

i) To select an appropriate 'brittle' weld metal to initiate running cracks within specified crack mouth opening displacement (CMOD) limits at the intermediate level of arrest toughness for the 350WT plate.

ii) To investigate the performance of UTP DUR 400 hardfacing electrode as an alternative, especially to be used at the lower arrest toughness at the NDTT when the success rate of Foxdur 500 was low.

At the intermediate test temperature (arrest toughness level) the Foxdur 350 weld starter was successful in providing a crack run within the CMOD limits with sufficient driving force to produce a successful run-arrest in the two specimens tested.

At the lower test temperature (arrest toughness level) all three tests gave premature initiation from the UTP DUR 400 weld bead. If the K_0 value of 102 MPa√m obtained for this starter weld bead from the initiation in the intermediate size specimen were taken into consideration, then the starter weld has borderline toughness for this specimen size with an anticipated $K_v = 95$ MPa√m.

7.0 RECOMMENDATIONS

i) Since the UTP DUR 400 electrode displayed a similar initiation toughness to the Foxdur 500, it could be considered as replacement for the latter electrode, which is no longer marketed in North America. However, since the five tests conducted on CCA specimens having UTP DUR 400 all led to premature initiation in the temperature range –40 to –20°C its usefulness would need to be further investigated.

ii) At the NDTT of this steel the success rate has been low (1 in 6) with Foxdur 500 and UTP DUR 400 brittle welds, primarily because of premature initiation using the specimen with W = 100 mm. Therefore, the possibility of improving the success by using a larger specimen size with Foxdur 350 weld starter also needs study.

iii) There is a need for an annex to extend the range of application of ASTM E1221 and provide guidance for full thickness crack arrest toughness tests, including advice on the selection of appropriate crack starter materials.

8.0 REFERENCES

1) "Crack arrest fracture toughness of steel weldments", Interim Report, Submitted to U.S. Coast Guard, September 1998.

2) L.N. Pussegoda: "Selection of brittle weld electrodes for crack arrest toughness determination", DREA Report CR 98/425, May 1998.

3) "Crack arrest toughness of a 350WT plate and its heat affected zone", DREA CR 98/416 January 1998.

4) P.B. Crosley & E.J. Ripling: " A quality control test for selecting materials to arrest fast-running full-thickness cracks", JTEV, 18, 1990, pp. 396-400.

Table I - Chemical Composition of Steel Plate, (wt%)

C	Mn	P	S	Si	Ni	V	Ti	Al	N
0.16	1.38	0.009	0.005	0.28	0.21	0.07	0.009	0.036	0.006

Table II - Test Matrix

Anticipated Arrest Toughness K_v (MPa√m)	Specimen Size W (mm)	T (°C)	Number of Specimens	Electrode
120	175	-25°	3	Foxdur 350
120	175	-25°	2	UTP DUR 400
94	100	-40°	3	UTP DUR 400

Table III - CCA Test Results.

ID	T (°C)	cycle	CMOD range (4)	W (mm)	a_a/W	K_v (MPa√m)	K_o (MPa√m)	K_a (MPa√m)	K^*_a (MPa√m)
10	-30	4	within	142	0.667	110	163	99	95
11	-30	5	within	142	0.721	110	174	97	93

K_v - anticipated crack arrest toughness

K_o - initiating stress intensity factor

K_a - full thickness crack arrest toughness calculated from linear elastic expression

K^*_a - crack arrest toughness after plasticity correction employed by Crosely & Ripling (4).

Table IV - Summary Results of the remaining Tests

I.D.	Crack starter	T (°C)	cycle	CMOD range(4)	W (mm)	K_v (MPa√m)	K_o (MPa√m)	K_a (MPa√m)	comments
1	Foxdur 350	-25	3	within	175	120	159	>120	crack run about 2 mm in base metal
2	Foxdur 350	-25	3	within	175	120	142	>120	crack run about 2 mm in base metal
3	Foxdur 350	-30	3	within	175	122	167	>122	crack run about 4 mm in base metal
4	UTPDUR 400	-20	1	below	175	120	-	-	crack only in brittle starter
5	UTPDUR 400	-20	1	below	175	120	102	-	crack only in brittle starter
6	UTPDUR 400	-40	1	below	100	94	-	-	crack only in brittle starter
7	UTPDUR 400	-40	1	below	100	94	-	-	crack only in brittle starter
8	UTPDUR 400	-40	1	below	100	94	-	-	crack only in brittle starter
9	Foxdur 350	-30	5	within	142	110	185	>110	crack stopped at the end of starter

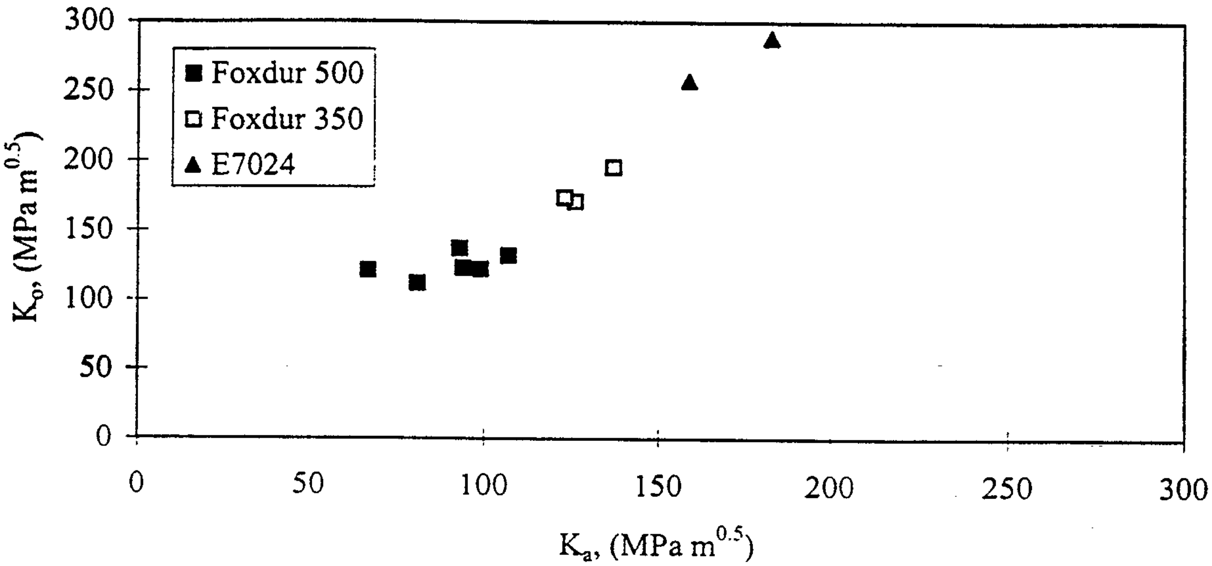
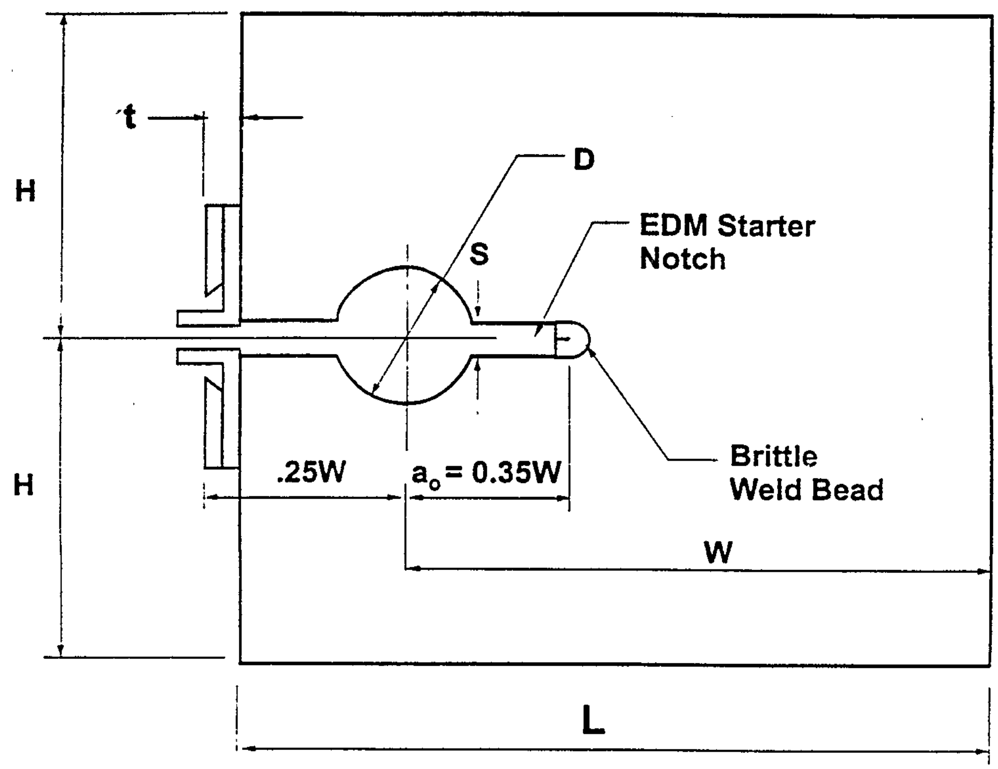


Fig 1 - Relation between crack arrest toughness (K_a) and initiating toughness (K_o).



H= 0.6W ± 0.005W
L = 1.25 - t
S≤ W/10

Fig 2 - Full thickness CCA specimen with proportionate dimensions and brittle weld bead.

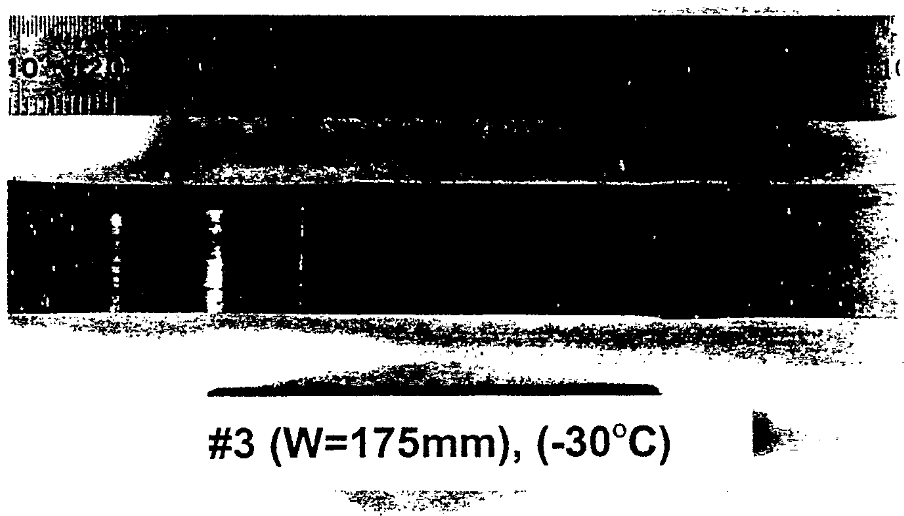
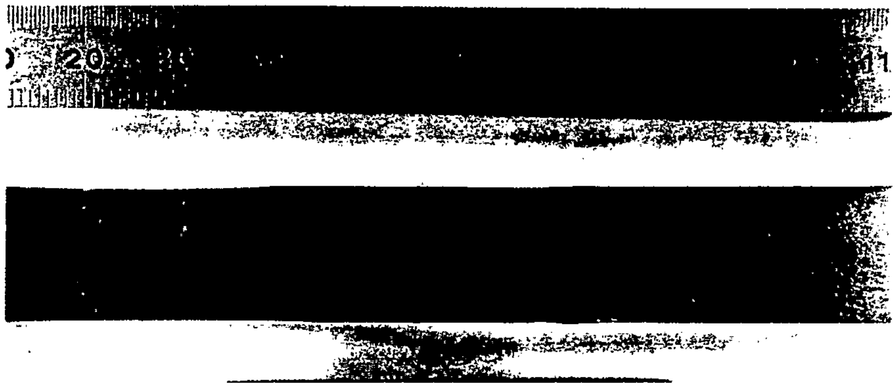
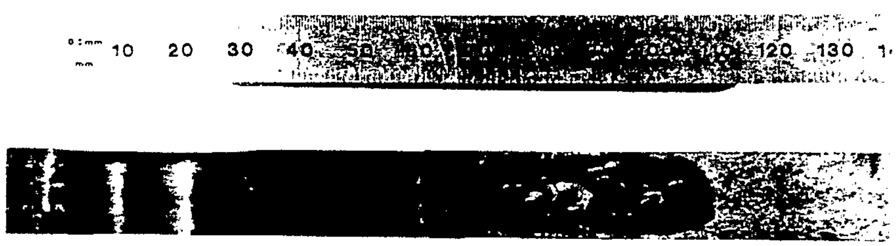


Fig. 3 -Fracture displaying the crack run (darker region) obtained from a W = 175 mm size specimen with a Foxdur 350 starter weld bead. Plate thickness 16.4 mm tested at –30°C.



#9 (W=142mm), (-30°C)

(a) 16.4 mm plate thickness



#10 (W=142mm), (-30°C)

(b) 15.5 mm plate thickness.

Fig 4 - Fractures from specimens with Foxdur 350 at –30°C.

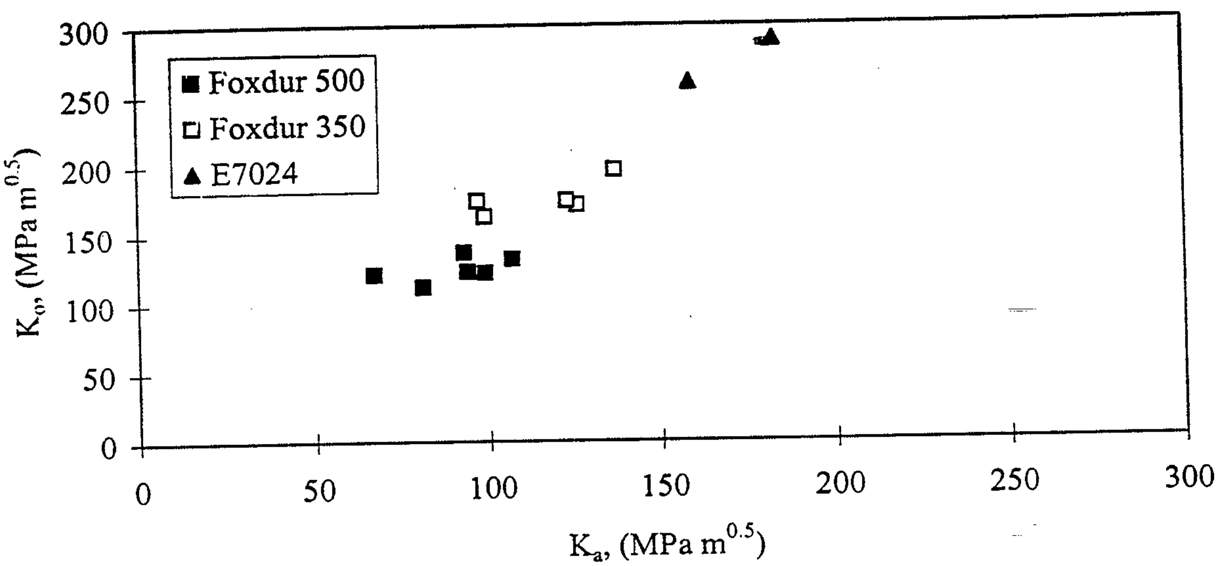


Fig 5 - Supplemented plot of crack arrest toughness (K_a) and initiating toughness (K_o).

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