Image Cover Sheet

CLASSIFICATION UNCLASSIFIED	**SYSTEM NUMBER** 509065

TITLE

SELECTION OF BRITTLE WELD ELECTRODES FOR CRACK ARREST TOUGHNESS DETERMINATION

System Number:

Patron Number:

Requester:

Notes:

DSIS Use only:

Deliver to:

National Defence
Research and
Development Branch

Défense nationale
Bureau de recherche
et développement

DREA CR 98/425
MAY 1998

SELECTION OF BRITTLE WELD ELECTRODES FOR CRACK ARREST TOUGHNESS DETERMINATION

L.N. Pussegoda

FLEET TECHNOLOGY LTD
311 Legget Drive
Kanata, Ontario, Canada
K2K 1Z8

CONTRACTOR REPORT

Prepared for

Defence
Research
Establishment
Atlantic

Centre de
Recherches pour la
Défense
Atlantique

Canada

PLEASE DIRECT ENQUIRIES TO:

THE DIRECTOR GENERAL
DEFENCE RESEARCH ESTABLISHMENT ATLANTIC
P.O. BOX 1012
DARTMOUTH, NOVA SCOTIA, CANADA
B2Y 3Z7

National Defence
Research and
Development Branch

Défense nationale
Bureau de recherche
et développement

DREA CR 98/425

SELECTION OF BRITTLE WELD ELECTRODES FOR CRACK ARREST TOUGHNESS DETERMINATION

L. N. Pussegoda

FLEET TECHNOLOGY LTD.
311 Legget Drive
Kanata, Ontario, Canada
K2K 1Z8

Scientific Authority

J. Morrison

W7708-7-0662
Contract Number

May1998

CONTRACTOR REPORT

Prepared for

**Defence
Research
Establishment
Atlantic**

**Centre de
Recherches pour la
Défense
Atlantique**

Canada

ABSTRACT

In crack arrest tests fast running cracks are usually initiated from either brittle weld deposits or strain age embrittled notches. A previous study of the crack arrest toughness of ship plate indicated that for different specimen sizes and material toughness, the crack starters need to have different degrees of embrittlement. For a successful test, larger and tougher specimens require a higher stored energy before crack initiation, and the crack starter should be able to delay triggering the crack run. Similarly, smaller less tough specimens need a lower stored energy. The suitability of several selected weld electrodes with different hardness and/or toughness has been assessed in terms of their ability to initiate running cracks. Two sizes of full thickness compact crack arrest (CCA) specimens with crack starter weld beads were machined from 15 mm thick 350WT ship plate. They were oriented L-T with W = 300 and 100 and an a_o/W ratio of 0.35. The anticipated crack arrest toughness values corresponding to the two specimen sizes were K_v = 155 and 95 MPa√m at -15 and -40°C, respectively. The results indicate that at the test temperatures the three most promising crack starters had toughness values of about 100, 180 and 270 MPa√m. For the larger specimen the ideal crack starter had the intermediate toughness. For the smaller specimen, the best starter option was the one with the lowest toughness.

RÉSUMÉ

Pour les essais d'arrêt de fissuration, les fissures de propagation rapide sont généralement initiées à partir des matières à fondre fragile ou des entailles fragilisées à cause du vieillissement par l'écrouissage. Dans une étude antérieure de la résistance d'arrêt de propagation de la tôle de navire, nous avons déterminé que, pour les éprouvettes de grandeur et de résistance de matière différentes, les générateurs de fissures doivent avoir des degrés de fragilisation différents. Pour un essai réussi, les éprouvettes plus grandes et plus résistantes exigent une énergie emmagasinée plus élevée avant l'initiation de la fissure, et le générateur de la fissure doit être capable de retarder le lancement de la propagation de fissuration. De façon semblable, les éprouvettes moins grandes et moins résistantes demandent un niveau d'énergie emmagasinée plus faible. Nous avons évalué la convenance de plusieurs électrodes de soudure aux duretés et/ou résistances différentes, en termes de leur capacité d'initier des fissures de propagation. Deux grandeurs d'éprouvettes compactes d'arrêt de propagation, d'épaisseur pleine et avec des perles de soudure pour initier des fissures, ont été usinées d'une tôle de navire 350WT, 15 mm d'épaisseur. Elles étaient orientées dans le sens L-T où W = 300 et 100, et le rapport a_o/W était 0.35. Les valeurs anticipées de la résistance d'arrêt de propagation correspondantes aux deux grandeurs d'éprouvettes étaient K_v = 155 et 95 MPa√m aux températures de -15 et -40°C. respectivement. Les résultats indiquent qu'aux températures d'essai, les trois générateurs de fissuration les plus prometteurs avaient les valeurs de résistance d'environ 100, 180 et 270 MPa√m. Dans le cas de l'éprouvette plus grande, le générateur de fissuration idéal avait la résistance intermédiaire. Dans le cas de l'éprouvette moins grande, le meilleur choix de générateur était celui à la résistance la plus faible.

DREA CR 98/425

Selection of Brittle Weld Electrodes for Crack Arrest Toughness Determination

Executive Summary

There are two principal approaches to the development of schemes for avoiding brittle fracture in welded structures such as warship hulls. The first attempts to prevent crack initiation or unstable crack extension by, on the one hand, ensuring adequate notch toughness and fatigue resistance in the steel plates and welds after assembly, and on the other, by ensuring structural robustness and minimizing the effect of sharp corners or other stress raisers, so excessive static or cyclic loads are eliminated. This requires that high standards of quality control and workmanship be used during construction, particularly with regard to welding. Even so, given normal shipyard limitations, it is difficult to ensure that the welds are free from local regions of low toughness or small crack like defects. Information on typical operating loads is often sketchy at best, and in the assessment of how critical a flaw may prove to be, it is usually difficult to quantify exactly the influence of stress concentrators and residual stresses. As a result it is usually necessary to adopt some very conservative assumptions about the applied stresses which can lead to very pessimistic estimates of tolerable flaw size.

The second approach is to employ materials which are capable of arresting running cracks. This requires that the "crack arrest toughness" is 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. In principle this is a simple concept, but in practice there are numerous difficulties in its application. Although in recent years improved test techniques for measuring the crack arrest performance of steels and welds have been developed, they are usually difficult to carry out and very expensive. There has also been considerable argument about the underlying theory of crack arrest, for example, whether or not the analysis of material behaviour requires a fully dynamic analysis. Thus except in some special applications crack arrest methodology has not been rigorously utilized. In recent years however, the availability of better instrumentation and more sophisticated structural analysis has increased the interest in crack arrest for a wider range of applications, including ships.

The work described in this report is part of an ongoing project to assess the suitability of applying crack arrest test methods to ship construction materials. An earlier report dealt with the measurement of arrest toughness in 350WT steel and heat affected zone. This report describes efforts to further optimize the initiation of a running crack in the test specimen, which is probably the most difficult requirement of the test method.

Table of Contents

1.0 Introduction

The plane-strain crack arrest toughness testing procedure in ASTM Standard E1221-96 is not suitable for naval structural steel plate. This is primarily because, given the limited plate thickness, the toughness is too high in relation to the strength to meet the constraint requirements of the test,.(1) Some success was achieved in an earlier project funded by the Dockyard Laboratory (Pacific) using a larger, non-plane-strain (full thickness) specimen in which a crack was initiated from a strain aged embrittled chevron notch.(1,2) However, recent experience has shown that this method of embrittlement is not suitable for all steels, in particular those subject to splitting in the short transverse plane, a tendency increased by the lateral compression used during strain age embrittlement. Further testing suggested that the more conventional 'brittle weld bead' crack starter approach might overcome this problem and offer a more generally applicable method for initiating a crack run event in non-plane-strain crack arrest toughness tests. The weld electrodes used previously for crack initiation from brittle weld beads are listed in Table I. However, it is not yet clear which electrode is the most suitable for a given situation.

Table I - Electrodes Used for Brittle Weld Bead Starters

Electrode Trade Name	Wire Diameter (mm)	Nominal Hardness (HRC)
Lincoln Wear Weld	-	50
Foxdur 500	5	50
Foxdur 350*	5	35
E7024	4	25

*also known as UTP DUR 350

Previous(2) work also suggested that the suitability of a given brittle bead weld metal might depend on the specimen size, and in turn on the arrest toughness. When high values of crack arrest toughness are to be measured (large specimen size), the specimen/weld bead combination should be able to store a greater amount of energy before the crack run event is triggered, which means that the weld should not be too brittle. Conversely, when the crack arrest toughness is expected to be low (smaller specimen size), a more brittle starter material may be required so that crack run events are initiated at low stored energies. The object of this investigation is to assess the suitability of selected weld electrodes with different hardness in terms of their ability to initiate running cracks within the crack mouth opening limits specified by the non-plane strain crack arrest procedure.(3) The test temperature was also varied to permit the determination of two levels of arrest toughness.

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 project with the composition shown in Table II. The measured crack arrest toughness in the L-T orientation, derermined using the embrittled chevron notch approach, was about 155 MPa√m at -15°C (specimen W = 300 mm, 5 valid results of 6 tests), and 93 MPa√m at -30°C (specimen W = 175 mm, 1 valid result of 3). Smaller specimens (W=100 mm) tested at -40°C or lower temperature did not provide any valid results.

Table II: 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

3.0 Design and Manufacture of Non-Plane Strain Specimens

Specimen sizes were determined according to the procedure outlined by Crosley and Ripling.(3). The test matrix for the non-plane strain crack arrest toughness measurement is given in Table III.

Table III. Test Matrix

Anticipated Arrest Toughness, (K_v). (MPa√m)	Specimen Size, W (mm)	T, (°C)	Number of Specimens	Electrode
155	300	-15°	3	Foxdur 500
155	300	-15°	3	Foxdur 350
155	300	-15°	3	E7024
94	100	-40°	3	Foxdur 500
94	100	-40°	3	Foxdur 350

For specimen size W = 300 mm, with K_v = 155 MPa√m, the selected starter material would require an initiation toughness in excess of 155 MPa√m. It was anticipated that Foxdur 500 weld bead would have a lower initiation toughness, while Foxdur 350 and E7024 would have higher values. The test matrix was developed to test this prediction. Similarly, the matrix for the smaller specimen with K_v = 95 MPa√m, was selected to verify the success of using a lower stored energy starter before the crack initiation. Following Crosley and Ripling the in-plane specimen dimensions are shown in Figure 1 in terms of W. The loading hole diameters (D) were respectively 50 mm and 31 mm for specimens with W = 300 mm and 100 mm. The slot geometry (L-T direction) was in accordance with ASTM E1221–96.

The two specimen geometries had W dimensions which were the largest and smallest of those used in the earlier EDRD project.(2) The only difference was the use of brittle weld beads rather than a strain aged chevron notch. It was anticipated that different electrodes would prove to be the most suitable at the two crack arrest toughness levels. For the reasons outlined above, the lower hardness weld metals (Foxdur 350 or E7024) were expected to perform better with the larger specimens tested at -15°C (higher toughness) whereas the Foxdur 500 electrode was expected to be more suitable for the smaller specimens tested at -40°C (with lower expected crack arrest toughness).

The brittle weld beads produced using the Foxdur 500 and 350 electrodes were deposited following ASTM E1221-96, Appendix IX.. For the E7024 electrode weld bead, pre-heat was not employed, but the remaining recommendations in Appendix IX were followed. In both cases, demagnetization was employed. The EDM notch was placed in the weld bead using a 0.010" wire to a depth of 2 to 4 mm, resulting in an a_o/W ratio of 0.35.

4.0 Crack Arrest Test Procedure

Loading was carried out in accordance with ASTM E1221-96. Teflon was used both on the split pin and also on support blocks and hold down plates. These reduce friction during loading and unloading cycles, and also insulate the specimen for temperature control purposes. The CMOD was measured using a calibrated clip gauge mounted on the specimen using the knife edges described in ASTM E 1221 so that the seating was not altered during the crack jump. The load was applied using a cross-head rate of 7.5 mm/min, and load vs. CMOD was recorded during the test using an X-Y plotter. During the tests up to 6 load cycles were employed. The increases in CMOD for the 5th and 6th cycles were the same. This modification resulted in a final CMOD which was slightly above that recommended in ASTM E1221. Above this limit, the stored energy was expected to be too high, thus a crack would run too far for that specimen size. This meant that the remaining ligament was insufficient to ensure a valid result. The CMOD limits suggested by Crosley and Ripling(3), within which a run-arrest event should occur for a successful test, were also marked on the test plots. Their lower value falls between the first and the second unloading limits of the ASTM procedure, while their upper value lies between the 5th and 6th unloading limits.

The load cycles were applied until the run-arrest event was detected, both audibly and by observation of an abrupt load drop. If this did not occur by the time the CMOD reached or just exceeded the upper limit of the 6th cycle, the specimen was unloaded and the test was discontinued.

4.1 Large Specimens (W = 300 mm)

All of these tests were conducted at -15°C. The temperature was measured by two spot welded thermocouples at two locations, one 25 mm from the root of the EDM notch and the other 40 mm from the back face of the specimen. The former was connected to a controller operating a solenoid that regulated the liquid nitrogen cooling spray. Once both temperatures were within ± 2°C of the desired value, the test was started.

In specimens which produced load drops the crack extension which occurred during the test was marked by heat tinting at about 300°C. They were then cooled in liquid nitrogen to produce a completely brittle fracture when broken open.

4.2 Small Specimens (W = 100 mm)

All of these tests were conducted at -40°C. The temperature was measured at 25 mm from the root of the EDM notch. This thermocouple was also connected to a controller, and the test started once the temperature had been within ± 2°C of the set value for ten minutes.

5.0 Results

The crack arrest test results are summarized in Table IV.

5.1 Large Specimens (W = 300 mm)

5.1.1 Foxdur 500 electrode bead.

In these specimens, a small discontinuity occurred in the load-CMOD trace during the 1st loading cycle. During this event there was no clearly audible pop, and the tests were continued in accordance with ASTM E1221. In one test (# 8) a run-arrest event occurred during the 4th cycle, whereas in the other two (#'s 7 and 9) this event took place during the 6th cycle; before reaching the upper limit in the case of specimen # 9 and at the upper limit in the case of specimen # 7. These three events all gave a significant load drop. For # 8 this was about 35% and for # 9 the drop in load was 50%.

5.1.2 Foxdur 350 electrode bead.

In all of these specimens, a run-arrest event occurred within or just above the lower CMOD limit suggested by Crosley and Ripling. In two tests (#'s 10 and 11), this occurred during the 3rd cycle, and in a third (# 12) it took place during the 2nd at the cycle CMOD limit. All of these events produced a significant load drop (≈ 30%).

5.1.3 E7024 electrode bead.

In two tests (#'s 13 and 14), the crack run occurred during the 6th cycle. In specimen # 13 it occurred before the upper CMOD limit suggested by Crosley and Ripling and in specimen # 14, just after the limit was exceeded. In the remaining specimen #15 no significant run-arrest event occurred during the 6th cycle. For specimens 13 and 14 the load drop was ≈ 50%.

5.2 Small Specimens (W = 100 mm)

5.2.1 Foxdur 500 electrode bead.

In specimen # 1, a run-arrest event occurred during the 2nd cycle, with a load drop of 40% at the lower CMOD limit suggested by Crosley and Ripling. The other two tests were taken up to the 6th cycle and discontinued at the CMOD limit without any audible event occurring. Observations made on the surface of the specimens showed that specimen # 1 had a significant crack run, while the other two displayed cracks only in the weld bead.

5.2.2 Foxdur 350 electrode bead.

All of these specimens were taken up to the 6th cycle, and the test discontinued at the CMOD limit of this cycle as no run-arrest event had occurred. Observations made on the surface of the three specimens showed that weld bead had not cracked.

5.3 Calculation of Crack Arrest Toughness

For specimens with crack runs, the arrest toughness was determined in accordance with ASTM E1221-96. In all of 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 Crosley and Ripling 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(2), and when the necessary conditions are met this value is reported as K^*_a in Table IV.

6.0 Discussion

6.1 Comparison with Strain Age Embrittled Chevron Starter

In tests carried out at -15°C, K^*_a values obtained in the present investigation range from 121 to 172 MPa$\sqrt{m}$. In the previous work, which employed chevron notch crack starters and a single loading cycle, the range was 123 to 172 MPa$\sqrt{m}$. Thus there appears to be no significant differences in measured arrest toughness. A detailed examination of the present tests resulted in the following observations:

a) The lowest crack arrest toughness values were obtained from specimens that had the Foxdur 350 weld bead. The corresponding crack initiating stress intensity factor K_o was the lowest; ranging from 171 to 196 MPa√m (Table IV). In all three specimens the crack runs were also the shortest (a_a/W range 0.50 to 0.55). A typical example is presented in Figure 2.

b) In the case of the other two electrodes a higher crack arrest toughness was obtained with a correspondingly higher crack initiating stress intensity factor K_o. The crack runs were also longer (a_a/W range 0.65 to 0.70, see Figures 3a and 3b).

The tunnelling observed on the heat tinted fracture surfaces presented in Figures 2 and 3 is to be expected in non-plane strain CCA specimens due to the absence of triaxial constraint at the two edges.(1,2) As a result, the main concern as to the acceptability of the arrested crack when evaluated using Annex A1 of ASTM E1221 is the amount of ligamentation. These ligaments are patches on the fracture plane which remained unbroken during the crack run event, and which are commonly observed on rapidly fractured surfaces. Taking into consideration the fact that these tests were done at 25°C above the NDTT of the steel(2), a 40% unbroken ligament area would be considered the upper limit at which the test result would be disregarded. Fortunately, none of the tests carried out in either the current or earlier program approached this amount of ligament in the crack run region.

Unbroken ligaments are allowed by Annex A1 at test temperatures above the NDTT because they could be representative of the actual behaviour of the material. These ligaments, when they are present in significant amounts in the crack run region, would effectively increase K_a by assisting earlier arrest. It is suggested in this Annex that "the only method of evaluating whether the degree of remaining ligaments on a given specimen is truly representative of the material behaviour at the test temperature of interest, is to perform a large number of tests under identical conditions, thereby establishing a baseline for observations." In this work an attempt to establish such a baseline has been done by analysis of all of the results from tests performed at -15°C. The results that meet the applicable validity requirements of ASTM E1221 have been reviewed, even though the crack starter conditions were different. All specimens with Foxdur 350 starter weld bead produced fractures without any unbroken ligaments (a typical fracture is shown in Figure 2) and gave the lowest crack arrest toughness values. The other specimens, except # 8, all displayed remaining ligaments and typical fractures are presented in Figure 3. Of these Specimen # 8 has the lowest arrest toughness. The baseline value determined from the specimens that do not have remaining ligaments is 131 MPa√m. All of the other specimens contain remaining ligaments and have a higher crack arrest toughness. The highest value of 172 MPa√m was obtained from the specimen with the largest amount of unbroken ligament.

The -15°C arrest toughness results from the previous program can be rationalized in a similar manner. The lowest value at 123 MPa√m did not have any unbroken ligaments, whereas, all the other specimens displayed remaining ligaments and consequently gave higher arrest toughness. Again the highest value was 172 MPa√m, obtained from the specimen that with the greatest ligamentation.

Only one result was obtained at -40°C, resulting in a K^*_a value of 66 MPa√m (Table IV). As would be expected, there is less tunneling when testing at the NDTT temperature than in the tests done at -15°C (Figure 4). Given that there are few unbroken ligaments, the above rationale suggests that this result should be close to the baseline arrest toughness at this temperature. Furthermore, there should be less scatter in arrest toughness at the lower temperature because the tests at -15°C were in the fracture transition range. The -40°C result was obtained from a specimen having the Foxdur 500 weld metal starter, whereas the strain age embrittled chevron starter was not successful at this test temperature. This result is also consistent with the trend shown in Figure 7 in the previous report.(2)

6.2 Suitability of the Various Crack Starter Materials (Table IV)

6.2.1 Tests conducted at -15°C

The behaviour during testing described in section 5.1 demonstrates that the weld bead starter materials covered a large range of initiation toughness values at this temperature. The applied stress intensity factor (K_o) at the maximum CMOD employed for the specimen size of W = 300 mm with an a_o/W ratio of 0.35 is about 290 MPa√m.

In the tests with Foxdur 500 starter bead, initiation occurred in the first cycle at an applied stress intensity factor (K_o) of about 95 MPa√m. Therefore the driving force was insufficient to run a crack in a base material having an arrest toughness of about 130 MPa√m or greater. This was a consistent finding for all three tests. A second event occurred at each of the arrested crack tips in the base material at a higher applied K_o (211 to 276 MPa√m) and thus resulted in a successful test. For specimen #8 the crack run took place in the 4th load cycle while for #'s 7 and 9 crack ran in the 6th cycle. Figure 5 shows the fractographic evidence for this two stage propagation. The applied K_o values reported in Table IV were determined using a modified a_o/W ratio to account for the initial extension.

By contrast, the Foxdur 350 with a higher initiation toughness delayed the first event to the second or third cycle. For a crack run to occur a K_o in the range 171 to 196 MPa√m had to be applied. This stress intensity was sufficient to drive the crack into a base material having an arrest toughness of 130 MPa√m or more, and resulted in a successful test.

The E7024 weld metal had the highest toughness of the starter materials investigated. In two of the tests initiation was delayed to the 6th cycle, while in the third (specimen # 15) the maximum K_o of 290 MPa√m was insufficient for initiation.

In summary, for this specimen size (W = 300 mm) and anticipated arrest toughness (K_v = 155 MPa√m) all starter weld beads gave a high rate of success in comparison to typical crack arrest testing experience. Only one specimen out of 9 did not provide a result. The tests carried out under similar conditions using the strain age embrittled chevron notch technique also had a high success rate. Overall, the best starter was the Foxdur 350 weld bead, since it produced a single event crack run into the base material at a sufficiently high K_o.

6.2.2 Tests conducted at -40°C

The applied stress intensity factor (K_o) at the maximum CMOD employed for the specimen size of W = 100 mm with a_o/W ratio of 0.35 is approximately 185 MPa√m.

The only test that produced a crack run had a Foxdur 500 starter bead. In this case (specimen # 1), initiation occurred during the second cycle at an applied stress intensity factor (K_o) of about 120 MPa√m. The two remaining specimens (#'s 2 and 3) did not produce any audible events, although observation showed a crack in the weld bead that terminated at the end of the weld. At the higher temperature the large specimens had provided a discontinuity during the first loading cycle at a calculated K_o of about 95 MPa√m, whereas this kind of event was not seen in the load traces from the smaller specimen #'s 2 and 3. If it is assumed that the brittle starter had an initiation toughness of about 100 MPa√m, and since at the CMOD limit at the end of the first load cycle the applied stress intensity was about 110 MPa√m, then a weld bead crack could have initiated during the first cycle. If this was the case the driving force may have been insufficient for the crack to run to the base material. The fractographic evidence (Figure 4) is that there was a single stage propagation for specimen # 1. Therefore for this specimen size (W = 100 mm), the Foxdur 500 starter appears to have a borderline initiation toughness which may delay the crack run to the second load cycle but also an arrest toughness (K_v = 95 MPa√m) which can produce a successful result from a first run-arrest event.

Foxdur 350 with a higher initiation toughness was not successful in initiating a crack, even at the maximum CMOD limit for this specimen design. At this CMOD limit the applied K_o is about 185 MPa√m. This value falls into the range of initiation stress intensity factors for the larger specimen using Foxdur 350 weld metal (171 to 196 MPa√m). This means that, in principle, it might be possible to initiate a crack at the maximum CMOD limit in the smaller specimen, even though it did not occur in practice. In order to improve the chances of a crack run event in these specimens an intermediate toughness weld metal needs to be employed.

7.0 Conclusions

The objective of this investigation was to provide guidance in selecting an appropriate 'brittle' weld metal to initiate running cracks within specified crack mouth opening displacement (CMOD) limits in the non-plane strain crack arrest determination procedure(3) at two levels of arrest toughness. The weld metals examined for this purpose were Foxdur 500, Foxdur 350 and E7024 (nominal hardness values: HRC 50, 35 and 25, respectively). The anticipated levels of crack arrest toughness (K_v) were 155 and 95 MPa√m.

a) At the higher test temperature (arrest toughness level) the ideal starter was the Foxdur 350 weld where the crack run occurred within the CMOD limits with sufficient driving force to produce a successful run-arrest in all three specimens. Although the other starter weld metals also had good success, in the harder Foxdur 500 the successful run-arrest event took place from the arrested crack tip positioned in the test material, whereas in the softer E7024 weld the run-arrest event occurred at the upper CMOD limit. These results are consistent since the Foxdur 500 weld produced an initial run-arrest event below the lower CMOD limit with insufficient driving force and therefore did not yield a result.

b) At the lower test temperature (arrest toughness level) only one successful run-arrest result was obtained. This was, as expected, in a specimen with a Foxdur 500 starter, resulting in a lower stored energy run event than at the higher arrest toughness level. If the K_o value of 95 MPa√m obtained for this starter weld bead from the first initiation in the large specimens were taken into consideration, then the starter weld has borderline toughness for this specimen size with an anticipated K_v = 95 MPa√m. To improve the success rate in these tests a higher toughness starter would be required. The Foxdur 350 was found to be too tough and was unsuccessful in initiating a crack run even when loaded to the upper CMOD limit in all three specimens. Beyond this limit, the driving force is expected to be too high to meet the validity requirements of the test.

8.0 Recommendations

For different reasons, neither of the two starter weld beads produced a good success rate for tests carried out using the smaller specimen. There is a need to investigate a starter weld bead having an intermediate hardness value between these two. One possibility would be the the UTP DUR 400 electrode made by the same manufacturer as the two hardfacing electrodes used for the current investigation which has the intermediate hardness of RC 40. In any case, according to Bohler Thyssen Welding Canada the Foxdur 500 is no longer marketed in North America.

9.0 References

1). L.N. Pussegoda, L. Malik and J. Morrison: “Measurement of crack arrest fracture toughness of a ship steel plate”, Jour. of Testing and Evaluation, JTEVA, in press.

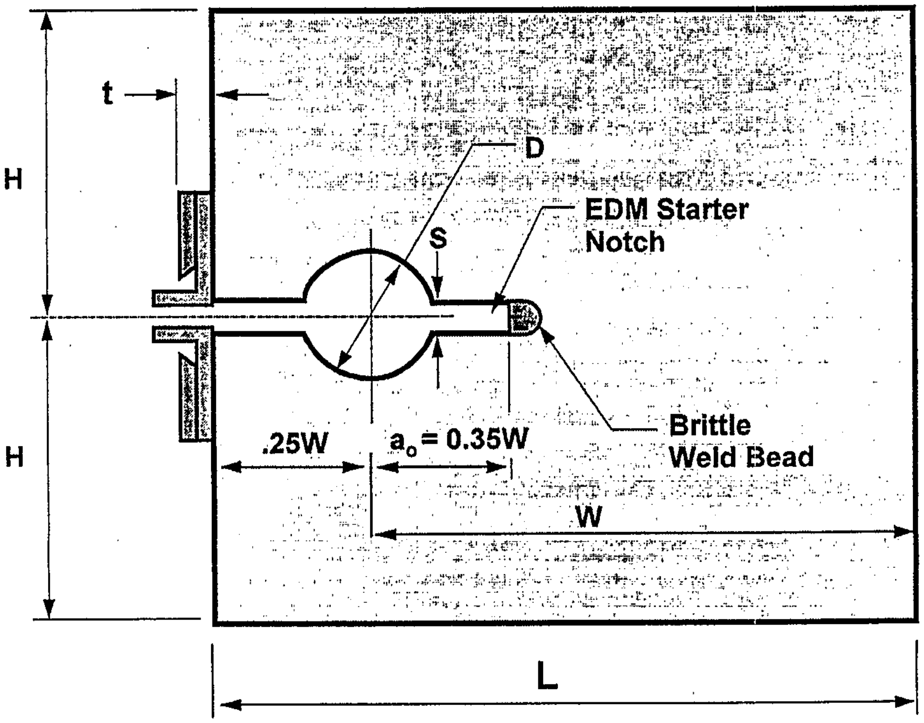
2). L.N. Pussegoda, “Crack arrest toughness of a 350WT plate and its heat affected zone”, DREA Contractor Report CR 98/416, January 1998.

3). P.B. Crosley & E.J. Ripling: “ A quality control test for selecting materials to arrest fast-running full-thickness cracks”, Jour. of Testing and Evaluation, JTEV, V.18, 1990, pp. 396-400

Table IV: CCA Test Results.

I.D.	Crack starter	T (°C)	cycle	CMOD range(3)	W, (mm)	a_o/W	a_a/W	K_v, (MPa√m)	K_o, (MPa√m)	K_a, (MPa√m)	K^*_a, (MPa√m)
1	Foxdur 500	-40	2	within	100	0.35	0.680	95	121	67	66
7	Foxdur 500	-15	6	exceed	300	0.37^+	0.719	155	276	168	157
8	Foxdur 500	-15	4	within	300	0.37^+	0.583	155	211	152	147
9	Foxdur 500	-15	6	within	300	0.36^+	0.688	155	246	155	148
10	Foxdur 350	-15	3	within	300	0.35	0.538	155	171	126	123
11	Foxdur 350	-15	3	within	300	0.35	0.564	155	174	123	121
12	Foxdur 350	-15	2	within	300	0.35	0.537	155	196	137	133
13	E7024	-15	6	within	300	0.35	0.698	155	258	159	152
14	E7024	-15	6	exceed	300	0.35	0.663	155	289	183	172

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 Crosley & Ripling(3)
$^+$ a_o takes the crack run in the first cycle into consideration



$H = 0.6W \pm 0.005W$
$L = 1.25 - t$
$S \leq W/10$

Figure 1: Full thickness CCA test specimen

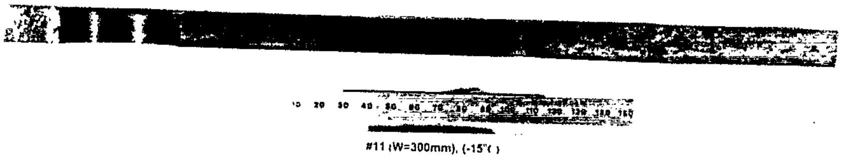
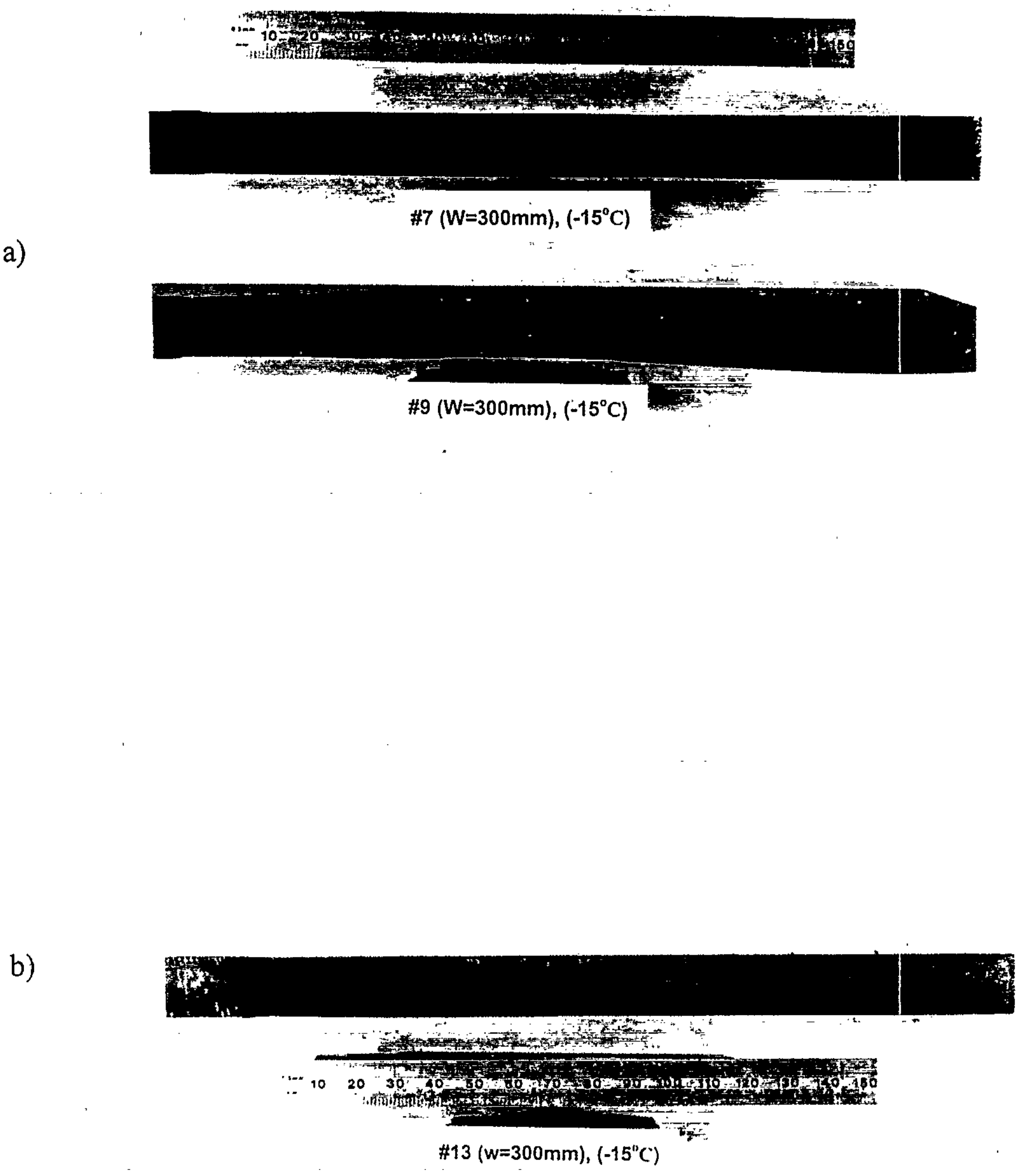


Figure 2: Fracture displaying a typical crack run (darker region) obtained from W = 300 mm size specimen with Foxdur 350 starter weld bead. (Neg No. 16462)



a)

#7 (W=300mm), (-15°C)

#9 (W=300mm), (-15°C)

b)

#13 (w=300mm), (-15°C)

Figure 3: Fractures from specimens with Foxdur 500 (a), and E 7024 starter weld bead (b). (Neg No.s 16463 & 16464)

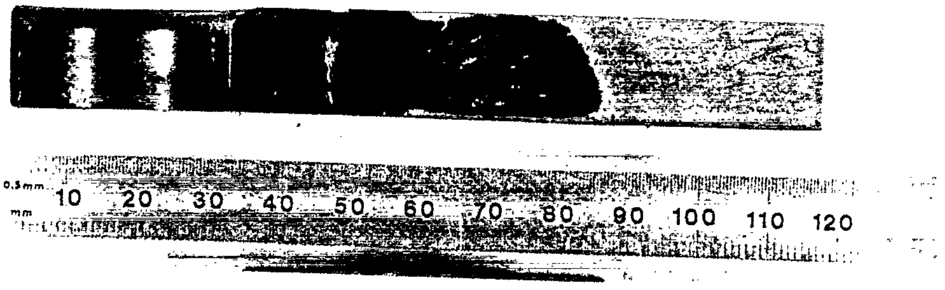


Figure 4: Fracture of the smaller specimen (W = 300 mm). (Neg No. 16461)

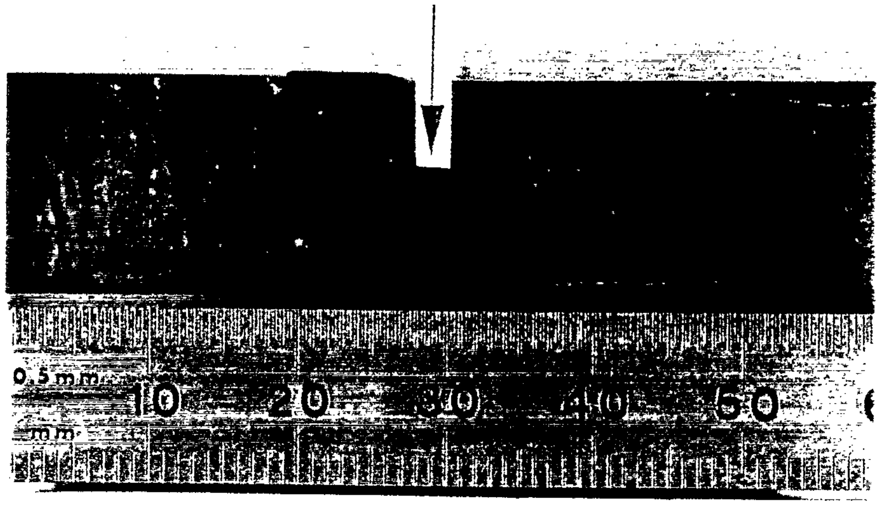


Figure 5: Fractures displaying propagation from the base metal indicated by arrow. Here the first event occurred with insufficient stored energy from Foxdur 500 weld bead. (Neg No. 16465)

UNCLASSIFIED
SECURITY CLASSIFICATION OF FORM
(highest classification of Title, Abstract, Keywords)

DOCUMENT CONTROL DATA

(Security classification of title, body of abstract and indexing annotation must be entered when the overall document is classified)

1. ORIGINATOR (the name and address of the organization preparing the document.. Organizations for whom the document was prepared, e.g. Establishment sponsoring a contractor's report, or tasking agency, are entered in section 8.)

Fleet Technology Ltd
3311 Leggatt Drive
Kanata, Ontario K2K 1Z8

2. SECURITY CLASSIFICATION (overall security classification of the document including special warning terms if applicable).

UNCLASSIFIED

3. TITLE (the complete document title as indicated on the title page. Its classification should be indicated by the appropriate abbreviation (S,C,R or U) in parentheses after the title).

Selection of Brittle Weld Electrodes for Crack Arrest Toughness Determination (U)

4. AUTHORS (Last name, first name, middle initial. If military, show rank, e.g. Doe, Maj. John E.)

Pussegoda, L.N.

5. DATE OF PUBLICATION (month and year of publication of document)

May 1998

6a. NO .OF PAGES (total containing information Include Annexes, Appendices, etc).

21

6b. NO. OF REFS (total cited in document)

3 references

7. DESCRIPTIVE NOTES (the category of the document, e.g. technical report, technical note or memorandum. If appropriate, enter the type of report, e.g. interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered).

CONTRACT REPORT

8. SPONSORING ACTIVITY (the name of the department project office or laboratory sponsoring the research and development. Include address).

Defence Research Establishment Atlantic
P.O. Box 1012, Dartmouth, Nova Scotia B2Y 3Z7

9a. PROJECT OR GRANT NO. (if appropriate, the applicable research and development project or grant number under which the document was written. Please specify whether project or grant).

9b. CONTRACT NO. (if appropriate, the applicable number under which the document was written).

W7708-7-0662

10a ORIGINATOR'S DOCUMENT NUMBER (the official document number by which the document is identified by the originating activity. This number must be unique to this document.)

DREA CR/98/425

10b OTHER DOCUMENT NOs. (Any other numbers which may be assigned this document either by the originator or by the sponsor.)

11. DOCUMENT AVAILABILITY (any limitations on further dissemination of the document, other than those imposed by security classification)

(X) Unlimited distribution
( ) Defence departments and defence contractors; further distribution only as approved
( ) Defence departments and Canadian defence contractors; further distribution only as approved
( ) Government departments and agencies; further distribution only as approved
( ) Defence departments; further distribution only as approved
( ) Other (please specify):

12. DOCUMENT ANNOUNCEMENT (any limitation to the bibliographic announcement of this document. This will normally correspond to the Document Availability (11). However, where further distribution (beyond the audience specified in (11) is possible, a wider announcement audience may be selected).

13. ABSTRACT (a brief and factual summary of the document. It may also appear elsewhere in the body of the document itself. It is highly desirable that the abstract of classified documents be unclassified. Each paragraph of the abstract shall begin with an indication of the security classification of the information in the paragraph (unless the document itself is unclassified) represented as (S), (C), (R), or (U). It is not necessary to include here abstracts in both official languages unless the text is bilingual).

In crack arrest tests fast running cracks are usually initiated from either brittle weld deposits or strain age embrittled notches. A previous study ofthe crack arrest toughness of ship plate indicated that for different specimen sizes and material toughness, the crack starters need to have different degrees of embrittlement. For a successful test, larger and tougher specimens require a higher stored energy before crack initiation, and the crack starter should be able to delay triggering the crack run. Similarly, smaller less tough specimens need a lower stored energy. The suitability of several selected weld electrodes with different hardness and/or toughness has been assessed in terms of their ability to initiate running cracks. Two sizes of full thickness compact crack arrest (CCA) specimens with crack starter weld beads were machined from 15 mm thick 350WT ship plate. They were oriented L-T with $W = 300$ and 100 and an a_o/W ratio of 0.35. The anticipated crack arrest toughness values corresponding to the two specimen sizes were $K_v = 155$ and 95 MPa$\sqrt{m}$ at -15 and -40°C, respectively. The results indicate that at the test temperatures the three most promising crack starters had toughness values of about 100, 180 and 270 MPa$\sqrt{m}$. For the larger specimen the ideal crack starter had the intermediate toughness. For the smaller specimen, the best starter option was the one with the lowest toughness.

14. KEYWORDS, DESCRIPTORS or IDENTIFIERS (technically meaningful terms or short phrases that characterize a document and could be helpful in cataloguing the document. They should be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location may also be included. If possible keywords should be selected from a published thesaurus. e.g. Thesaurus of Engineering and Scientific Terms (TEST) and that thesaurus-identified. If it not possible to select indexing terms which are Unclassified, the classification of each should be indicated as with the title).

steel
ships
toughness
welds
crack arrest
crack initiation
brittleness