THE APPLICATION OF THE DOUBLE TORSION TESTING TECHNIQUE TO ELECTROSLAG REMELTED HIGH STRENGTH STEELS

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ABSTRACT

The Outwater Double Torsion Test (ODT) has been applied to a wide variety of materials since its inception in 1965. The present paper describes its application to evaluating the variation of fracture toughness with orientation in an electroslag remelted (ESR) AISI 4340 steel (H_{RC} 57).

As well as charting changes due to orientation, the paper describes the effects of the application of fatigue pre-cracking, as well as its absence in testing. Experiments with miniature ODT specimens were also undertaken in the investigation. The great utility of this testing technique for cases where sample material is available only in limited section sizes is emphasized.

INTRODUCTION

Electroslag remelting of alloy steels is generally recognized as presenting a means of minimizing and refining the population of non-metallic inclusions and thus providing an increased level of performance [1].

The evaluation of the mechanical and fracture related properties of such materials, performed in order to substantiate such claims, has been under study at the Georgia Institute of Technology supported by the U.S. Army Materials and Mechanics Research Center for a number of years. Of particular interest to the Materials Processing Group at Georgia Tech has been the assessment of such properties in sections of 25 mm and less [2].

The Outwater Double Torsion Test (ODT), which has been employed in this investigation, lends itself to the determination of fracture toughness of materials available in section sizes less than 25 mm [3]. Using this test, which itself has also been studied in detail by the Georgia Tech group [4], the authors describe how the fracture toughness of 10, 25 and 45 mm plate ESR 4340 (H_{RC} 57) has been determined.

EXPERIMENTAL BACKGROUND

The material utilized in the present investigation was drawn from two parallel heats of ESR 4340 material. The processing history of the heats has been described in a recent publication [5]. As well as ODT blanks, material for standard tensile and double ligament test (DLT) bars were taken in order to reveal the effects of orientation upon the yield, ultimate strength and elongation properties of the plates concerned.

The relevant mechanical properties of those plates, numbered S-I, S-II, and S-III (10, 25 and 45 mm thickness) are shown in Table 1. The associated heat treatment was carried out in a controlled atmosphere furnace according to the following steps:

1. Normalize at 900°C (1650°F) for 1 h, followed by air cooling.
2. Austenitize at 845°C (1550°F) for 1 h, followed immediately by oil quenching.
3. Temper at 170°C (340°F) for 1 h, followed by oil quenching.

Specimens were then fabricated by grinding under strictly controlled conditions. The average hardness of the material concerned, determined at the surface of the ground specimen, was generally in the range 55-57 H_{RC}.

The tensile bar data corresponded well with that determined by the DLT method [5]. However, it is to be noted that such comparisons can only be afforded in the longitudinal and long-transverse direction. The DLT data, therefore, reveals some important information on the ductility in the short-transverse or through-thickness direction. It will be seen that an important difference exists between the longitudinal and long-transverse direction ductility and ultimate strength values on one hand and those of the short transverse direction on the other. Further, fractographic related work on the materials concerned led the authors to conclude that a localized colonization of inclusions was present in the materials concerned. This state of affairs persisted in spite of the fact that the total volume fraction of inclusions was indeed low as one is led to expect with ESR material.

The double torsion test bars were fabricated from material adjacent to that used in the DLT and tensile tests. One of the most important geometric features of the ODT test is the thickness between the upper and lower grooves, referred to elsewhere as the non-grooved thickness or the fracture surface thickness, t_c. The bulk of the experience of previous work completed at the time of testing indicated that t_c should be equal to or greater than three to four times the expected plane stress plastic zone size [6].

Two sets of ODT specimens were prepared. One set possessed a non-grooved thickness of 9.5 mm, the second a corresponding thickness of 5.1 mm. The grooved thickness (t_c) values were respectively 7.0 and 3.7 mm. Both sizes met the above t_c criteria. Each specimen had in addition to the usual grooving a starter notch (see Figure 1). This feature had been added to the original ODT geometrical requirements (see Reference 3) as a result of a finite element analysis [4] which revealed the presence of end effects. The work concerned suggested that a starter notch or pre-crack length should obey the criteria:

$$C \geq 0.35\ W$$

$$L - C \geq 0.65\ W$$

where L is the length overall, C the crack length and W the specimen width. Use of the starter notch permitted the determination of K_Q values free from end effects. All such K_Q determinations commenced with the sharpening of the starter notch by fatigue pre-cracking. The applied loads to produce the sharpened crack were cycled between 0.1 and 0.6 of the expected critical load P_c. After the fatigue pre-cracking, the test was commenced in the manner previously described [3]. A limited number of specimens were inverted after the initial pre-cracking and a second pre-crack initiated, thus producing a chevron rather than a semi-elliptical pre-crack shape. Two values of K_Q can be obtained during ODT testing: firstly from those P_c values associated with fatigue pre-cracking and secondly from those associated with an immediate re-initiation of any new crack from one previously propagated. The K_Q values for both nonfatigue (Nf) and fatigue pre-cracked situation (f) are recorded in the tabulated results. By arresting the crack, as many as five pairs of readings could be obtained. A variety of crack orientations were also studied. The exact combination depended upon the plate sample dimensions.

RESULTS

Table 2 represents a typical recording of ODT test data obtained from using a 10,000 lb* Instron machine. Also shown in Figure 2 is an actual load-displacement curve obtained whilst testing an ODT specimen. Further details may be drawn from this recorded data.

Table 3 tabulates the observations made upon the various specimens. This table includes, in particular, the minimum and maximum value of fracture toughness, K_Q, for fatigue and nonfatigue pre-cracked specimens. It also indicates for each specimen from how many observations a particular average of K_Q value was derived.

Tables 4 and 5 contain averages, or weighted averages, of fatigue and nonfatigue pre-cracked K_Q values for each plate w.r.t. a particular crack plane orientation, for regular ODT and miniature ODT specimens, respectively.

Table 6 contains observations made whilst testing those miniature size ODT specimens which contained a chevron shaped pre-crack. The results are compared with those obtained from procedure followed elsewhere in which fatigue pre-cracking yields an elliptical-arc crack front.

Figure 3 summarizes all the important details of the experimental observations. It is a mean bar chart in which minimum and maximum of fatigue and nonfatigue pre-crack fracture toughness values, for both regular and miniature ODT specimens, are indicated with respect to the plate and the crack plane orientation. Results obtained from some companion CT tests are included in this figure to facilitate the comparison with ODT results.

DISCUSSION AND CONCLUSIONS

The results displayed in Tables 2-6 and summarized in Figure 3 shed considerable light upon the usefulness of the ODT test in evaluating high strength materials available in the form of plate. Firstly, regarding the effects of orientation, although no dramatic differences were seen to exist between longitudinally or short-transverse oriented specimens, the large number of data points obtained for the small volume of material sampled permits a good statistical coverage of the material concerned. In view of the colonization of inclusions referred to earlier in discussing the DLT experiments, this was clearly a desirable feature of the ODT work. The ranges of K_Q values tabulated are thus as important here as the average values shown (Table 7). It will be seen, for example, that with the full-sized ODT specimens, the ranges of the T-L or long transverse K_Q results are greater than those of the L-T or longitudinal specimens for the thinner section materials S-I and S-II. From the results of the miniature ODT tests on the thickest material S-III, however, one sees a significant difference ($\sim$14%) between the inplane (T-L and L-T) K_Q values on one hand and those of the S-T (short transverse) direction on the other. Again, this is as would be anticipated in any plastically worked material containing a dispersion of deformable nonmetallic phases.

Turning to the limited number of tests concerned with the chevron-type pre-cracked material, it will be seen that the K_Q values obtained are approximately 12 percent lower than those obtained with the usual elliptical arc shaped crack. If one were to presume that the same ratio would hold

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*4.48 kN

true for the material drawn from plate S-I then it would seem that the results of miniature ODT test with these two types of pre-crack probably bracket the ASTM approved CT result. However, further work would be required to confirm this.

Finally, addressing the question of the presence of the use of fatigue pre-cracking, or its absence, the majority of the conclusions drawn above could well have been arrived at from the non-fatigue pre-cracked results. This reinforces the original contention of Outwater and colleagues [3] that pre-cracking by fatigue is not a requirement for the ODT test. However, it should be noted that the initial pre-cracking phase is made extremely convenient by sharpening the starter notch by fatiguing. Once more it is interesting to note that the fatigue pre-cracked K_Q value for the full-sized ODT specimens is, as an overall average, 0.96 of the average of those determined using a fatigue type pre-crack. The overall average ratio of K_Q values obtained without fatigue pre-cracking to that of those obtained with fatigue pre-cracking for the miniature specimens is 0.95. This fact also supports the original contention of Outwater et al [3] referred to above regarding fatigue pre-cracking.

In all, it is believed that the investigation, as well as illustrating some important points regarding the ESR practice with 4340 type materials, indicates the very considerable utility of the ODT test where sample material is either in short supply or available only in limited section sizes.

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Table 1. Summary of Mechanical Property Averages Determined by DLT Test for Specimens from Different Plates of ESR AISI 4340 Steel ($H_{RC} \simeq 57$) with Respect to Orientation.

	Orientation								
	TX			LY			TZ and LY		
Plates	Yield Strength (σ_{ys}). MPa (ksi)	Ultimate Tensile Strength (σ_{UTS}). MPa (ksi)	Elongation %	Yield Strength (σ_{ys}). MPa (ksi)	Ultimate Tensile Strength (σ_{UTS}). MPa (ksi)	Elongation, %	Yield Strength (σ_{ys}). MPa (ksi)	Ultimate Tensile Strength (σ_{UTS}). MPa (ksi)	Elongation, %
S-I	1422 (206.3)	2115 (306.7)	11.6	1381 (200.3)	2144 (311)	12.9	1395 (202.3)	1966 (285.1)	7.4
S-II	1401 (203.2)	2176 (315.6)	12.2	1425 (206.7)	2262 (328)	13.6	1400 (203.1)	2108 (305.8)	8.8
S-III	1439 (208.7)	2253 (326.8)	13.5	1433 (209.3)	2161 (313.38)	12.6	1442 (209.2)	2122 (307.7)	7.9

TX - Longitudinal LY - Transverse TZ and LY - Short Transverse

(After Reference 5.)

TABLE 2

SAMPLE OF DATA RECORDING:
DOUBLE TORSION TEST RESULTS
Specimen 9, Plate S-III, CPO: T-L

AVERAGE VALUES

$P_c(f)$ = 5410 lbf

$P_c(Nf)$ = 5560 lbf

$K_Q(f)$ = 64.75 ksi$\sqrt{in}$

$K_Q(Nf)$ = 66.54 ksi$\sqrt{in}$

$\frac{K_Q(f)}{K_Q(Nf)} = 0.973$

DIMENSIONS

W = 2.587 in. L = 5.05 in.

W_m = 2.025 in. t = 0.375 in.

t_c = 0.275 in.

CALCULATIONS

I_p = 0.0186 in.^{4*}

$K_Q = (11.969)P_c$

FATIGUE LIMITS: P_1, Lower: 450 to 580 lb

P_2, Upper: 2850 to 3000 lb

FREQUENCY: 30 cpm

TOTAL CYCLES: 39,600

TIME, HRS.		0	14	16	18	20	22
Propagation load, lbf	$P_c(f)$	6000	5300	5350	5400	5500	5500
	$P_c(Nf)$		5400	5500	5600	5600	5700
Estimated K_Q(ksi$\sqrt{in}$)	(f)	--	63.43	64.03	64.63	65.82	65.82
	(Nf)		64.63	65.82	67.02	67.02	68.22

Final Fracture

Initial Sound:	5700 lbf
Peak:	6800 lbf
Completed:	5700 lbf

(f) Indicates fatigue precrack present.
(Nf) Indicates fatigue precrack not present.

*Polar moment of inertia of one-half of specimen.

$P_cN = 4.448 \ (P_c \text{ lbf})$

K_Q MPa$\sqrt{m}$ = 1.099 (K_Q ksi$\sqrt{in.}$)

TABLE 3

RESULTS FOR BOTH REGULAR AND MINIATURE SIZE
ODT SPECIMENS OF ESR-AISI 4340 STEEL ($H_{RC} \approx 57$)

Specimen #	Plate	Crack Plane Orientation	Minimum K_Q ksi$\sqrt{in}$		Maximum K_Q ksi$\sqrt{in}$		Average K_Q ksi$\sqrt{in}$	
			(f)	(Nf)	(f)	(Nf)	(f)	(Nf)
REGULAR SIZE ODT								
2	S-I	T - L	58.40	61.98	64.36	66.75	62.00^{5*}	64.72^{5}
3	S-I	L - T	58.65	62.24	60.44	68.22	60.80^{5}	64.78^{4}
4	S-I	L - T	65.83	67.02	65.83	67.02	65.83^{4}	67.02^{3}
5	S-II	T - L	51.46	53.86	62.24	62.83	56.97^{5}	59.50^{5}
6	S-II	L - T	58.65	59.84	65.83	67.02	62.00^{5}	63.20^{5}
7	S-III	T - L	58.25	59.85	61.00	61.00	58.00^{4}	60.25^{3}
8	S-III	L - T	58.88	62.48	63.43	67.02	61.25^{4}	64.51^{4}
9	S-III	T - L	63.43	64.63	65.82	68.22	64.75^{5}	66.54^{5}
10	S-II	T - L	59.84	60.80	64.24	63.43	61.04^{3}	62.15^{3}
11	S-II	L - T	56.25	61.34	59.84	61.34	57.15^{4}	61.34^{1}
MINIATURE								
D	S-III	L - T	54.12	57.07	57.40	59.04	55.50^{3}	57.80^{3}
F	S-III	T - L	57.40	59.86	60.68	65.27	58.75^{3}	61.95^{3}
H	S-I	T - L	57.40	59.86	59.04	61.50	58.40^{3}	60.70^{3}
I	S-I	L - T	59.04	60.70	59.04	60.70	59.04^{3}	60.70^{3}
J	S-III	S - T	50.84	52.48	52.48	55.76	51.38^{3}	54.12^{3}

* Average taken from given number of observations.
(f) Fatigue precracked
(Nf) Non fatigue precracked

K_Q MPa$\sqrt{m}$ = 1.099 (K_Q ksi$\sqrt{in.}$)

TABLE 4

SUMMARY OF ODT TEST RESULTS FOR REGULAR SIZE SPECIMENS
W.R.T. PLATE AND CRACK PLANE ORIENTATION.
MATERIAL--ESR-AISI 4340 STEEL ($H_{RC} \approx 57$)

PLATE \ CPO*	L - T K_Q ksi$\sqrt{in.}$		T - L K_Q ksi$\sqrt{in.}$	
	Fatigue Precracked	Non-fatigue Precracked	f	Nf
S-I	63.03	65.74	62.00	64.72
S-II	59.80	62.90	58.50	60.50
S-III	61.25	64.51	61.75	64.18

* CPO - Crack Plane Orientation K_Q MPa$\sqrt{m}$ = 1.099 (K_Q ksi$\sqrt{in.}$)

TABLE 5

SUMMARY OF ODT TEST RESULTS FOR MINIATURE SIZE SPECIMENS
W.R.T. PLATE AND CRACK PLANE ORIENTATION.
MATERIAL--ESR-AISI 4340 STEEL ($H_{RC} \approx 54$)

PLATE \ CPO*	L - T K_Q ksi$\sqrt{in.}$		T - L K_Q ksi$\sqrt{in.}$		S - T K_Q ksi$\sqrt{in.}$	
	f	Nf	f	Nf	f	Nf
S-I	59.04	60.70	58.40	60.70	--	--
S-II	--	--	--	--	--	--
S-III	57.80	55.5	58.70	61.90	51.40	54.10

*CPO - Crack Plane Orientation K_Q MPa$\sqrt{m}$ = 1.099 (K_Q ksi$\sqrt{in.}$)

TABLE 6

RESULTS OF TESTS USING MINIATURE ODT SPECIMENS WITH
CHEVRON AND ELLIPTICAL PRECRACKS--PLATE S-III
WITH CPO AS L-T, MATERIAL--ESR-AISI 4340 STEEL ($H_{RC} \approx 57$)

SPECIMEN	FATIGUE PRECRACK GEOMETRY	MINIMUM K_Q ksi$\sqrt{in.}$		MAXIMUM K_Q ksi$\sqrt{in.}$		AVERAGE K_Q ksi$\sqrt{in.}$	
		f	Nf	f	Nf	f	Nf
B, C, G	CHEVRON	44.3	47.56	50.8	54.12	48.5^{9*}	51.98^{9}
D	ELLIPTICAL	54.12	57.07	57.40	59.04	55.5^{3}	57.8^{3}

* Average of so many observations. K_Q MPa$\sqrt{m}$ = 1.099 (K_Q ksi$\sqrt{in.}$)

TABLE 7

RANGES OF K_Q VALUES OBTAINED USING ODT TEST
(REFER TO TABLE 3)

SPECIMENS #	PLATE	CRACK PLANE ORIENTATION	RANGE OF K_Q VALUES* ksi√in.	MPa√m
2	S-I	T - L	5.96	6.55
3 & 4		L - T	0.90	0.99
H	S-I+	T - L	3.80	4.18
I		L - T	0.60	0.66
5 & 10	S-II	T - L	7.59	8.34
6 & 11		L - T	5.38	5.91
7 & 9	S-III	T - L	2.57	2.82
8		L - T	4.95	5.44
F	S-III+	T - L	3.28	3.61
D		L - T	2.73	3.00
J		S - T	1.64	1.80

* Of fatigue pre-cracked values, $K_Q(f)$

\+ Miniature specimens

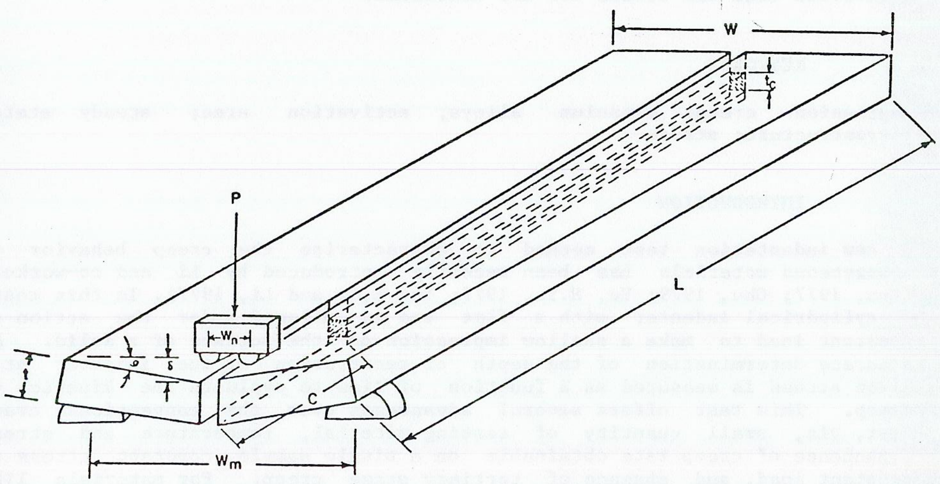
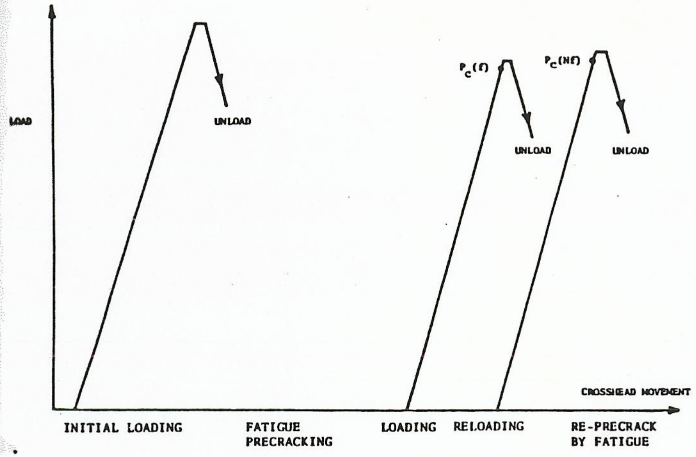


Figure 1. Appearance of a double torsion specimen under loading conditions.
NOTE: Both square section and 45° vee-grooves may be used. Present investigation employed latter.



LOAD DATA

Time hr.	$P_c(f)$ lb.	$P_c(Nf)$ lb.
0	No cracking at 6000 lb.	
14	5300	5400
16	5350	5500
18	5400	5600
20	5500	5000
22	5500	5700

$P_c N = 4.448 (P_c\ lbf)$

SCALE: ½ full size

Figure 2. Record of Crack Extension Load Data, AISI 4340 ESR $P_c(f)$ for Fatigue Precracking and $P_c(Nf)$ for Non-Fatigue Precracking (Crosshead Speed 0.02 in./min., Chart Speed 0.2 in./min.)

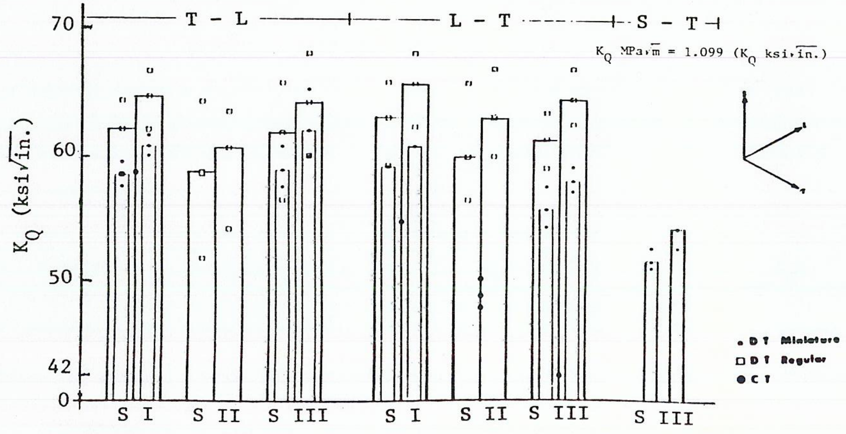


Figure 3. Fracture Toughness of [ESR] AISI-4340 Steel Using Double Torsion and Compact Tension Test Methods