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REPORT

MRL-R-831

A 'C'-SHAPED FRACTURE TOUGHNESS SPECIMEN FROM THE
WALL OF A 5"/54, MK 64, NAVAL PROJECTILE

D.S. Saunders

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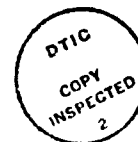
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The practical aspects of specimen preparation and testing have been assessed in this work.



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The practical aspects of specimen preparation and testing have been assessed in this work.

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A 'C'-SHAPED FRACTURE TOUGHNESS SPECIMEN FROM THE
WALL OF A 5"/54, M66, NAVAL PROJECTILE

1. INTRODUCTION

The trend for most new-generation artillery projectiles to be finely fragmenting has been responsible for the relatively low fracture toughness of the heat treated shell; usually less than 70 MPa m^{1/2}, Saunders (1980). This property of the shell steel is of primary importance in the design and manufacture of large calibre projectiles to ensure safety-of-launch and ability to withstand rough handling, Mulherin et al. (1976) and Saunders (1979). When manufacturing projectiles from low-toughness steels, it is important that the fracture toughness of the steel be known accurately so that defect inspection requirements can be specified.

For these reasons it is likely that the fracture toughness testing of locally-manufactured projectiles may become necessary to conform with overseas inspection criteria currently being assessed, Bruggeman (1979). There is a need, therefore, to investigate fracture toughness specimen configurations which may be suitable for application to certain large-calibre artillery projectiles. This Report is a preliminary investigation of a 'C'-shaped specimen configuration which may be taken from a thick-walled projectile.

2. AIM

The aim of the work reported here is to investigate the suitability of the 'C'-shaped specimen configuration for the fracture toughness testing of large calibre artillery projectiles. The specimen configuration follows that developed by Watervliet Arsenal, see Section 3.3, and independently studied by Ritter and Rea (1977).

3. EXPERIMENTAL

At the time of the initiation of this work there were no high fragmentation projectiles available for extensive testing, and so, to test the suitability of the 'C'-shaped specimen configuration the 5"/54 HE naval projectile was used. Within the limitations of projectile diameter and wall thickness, 'C'-shaped specimens from the 5"/54 and the UK L15A1 155 mm projectile are of comparable geometries, see Figure 1 (a and b). Thus, the specimen taken from the 5"/54 is a reasonable approximation of a fracture toughness specimen which could be taken from a typical new-generation high fragmentation projectile, see also Table II. The practical aspects of specimen preparation and testing were assessed in this work.

3.1 Material

The Australian 5"/54 projectile is manufactured from steel conforming broadly to the UK Ministry of Defence Standard 13-47 (1971).^{*} The composition specification is given in Table I.

3.2 Heat Treatment

The 'C'-shaped specimens taken from the projectile were heat treated to cover a range of toughness states approximately corresponding to those of the new-generation steels in high fragmentation projectiles, see Saunders (1980).

The heat treatment consisted of austenitizing at 850°C for 1/2 h, an iced brine quench, immediately followed by tempering. The tempering temperatures used were 300, 350, 400, 470, and 510°C and thus produced a range of yield strength states broadly representative of high fragmentation steels. Such heat treated conditions are, of course, not representative of the yield strength state specified for the production of 5"/54 naval projectiles.

3.3 Specimen Design and Fracture Toughness Testing

The 'C'-shaped specimen taken from the projectile was based on that proposed by Underwood and Kendall (1974), where the 'C'-shape used the inner and outer walls of a hollow cylinder to allow "economy of specimen fabrication and maximum utilization of the available wall thickness". Hence, for a series of differently sized cylinders (or artillery projectiles) the family of specimens can be defined in terms of the variable inner-to-outer radius ratio, r_1/r_2 , and the loading pin locations, X/W see Figure 2. X/W is usually fixed at 1 or 0.5. The stress intensity, K , calibration for a specimen is a series expansion incorporating the three specimen geometry variables, viz r_1/r_2 , X/W

^{*} See also Ordnance Factory Maribyrnong, Specification No. SF-1 (1978).

and a/W , where $a = (a_i + a_{\text{fatigue}})$ which is the crack length after fatigue pre-cracking, W is the wall thickness of the projectile or ring width of the 'C'-shaped specimen ($r_2 - r_1$) and X is load point location with respect to the intersection of the inner surface of the ring and the crack plane.

Two calibrations for the 'C'-shaped specimen have been proposed by Underwood and Kendall. The earlier calibration (1974) was developed for specimens with loading pin holes located on a radius defined by ($r_2 - .4W$), see Figure 2. However, the calibration used in the standard ASTM E 399/78 is based on the boundary value collocation results of Underwood and Kendall (1976, 1978). The specimen geometry used here was slightly different to that of the earlier work. The loading pin holes were located on a radius defined by ($r_2 - .25W$), see also Figure 2.

It should be noted that the 1974 and the 1978 calibrations yield slightly different $KB \sqrt{W/P}$ values for similar a/W values and eccentricity of loading points (P is applied load). Typical values are given in Table II, for both the 5" 'C'-shape and a 155 mm 'C'-shape specimens.

For this preliminary study of the 'C'-shaped specimens the 1974 specimen design was used, see Figure 2. However, to ensure that a representative slice of projectile was tested and that the specimen represented a projectile wall with an internal longitudinal crack, the thickness of the specimen, B , was double that recommended in the ASTM standard. Loading pin holes were located on a radius defined by $r_2 - .4W$.

The 1974 calibration for the stress intensity factor was used in this work, viz:

$$K = \frac{P}{B\sqrt{W}} \left[1 - 0.0126/\ln\left(\frac{r_2}{r_1}\right) \right] \left\{ 9.775 \left(\frac{a}{W}\right)^{1/2} + 29.01 \left(\frac{a}{W}\right)^{3/2} - 31.62 \left(\frac{a}{W}\right)^{5/2} - 27.45 \left(\frac{a}{W}\right)^{7/2} + 144.9 \left(\frac{a}{W}\right)^{9/2} \right\}$$

for $X/W = 0.5$

where B = specimen thickness
 W = specimen width, ($r_2 - r_1$)
 P = force
 a = crack length, ($a_i + a_{\text{fatigue}}$)
 X = eccentricity of load
 r_1 = inner radius
 r_2 = outer radius

For a narrow range of specimen geometry variables, a/W values between 0.45 and 0.55 and r_2/r_1 between 1.2 and 3.0, the above equation was considered to fit the collocation data of Underwood, Scanlon and Kendall (1974) to within 0.5%.

The testing procedure for the 'C'-shaped specimens conformed to ASTM E399/78. A BISRA* clip gauge, located on knife edges across the mouth of the notch, was used to measure the crack opening displacement. The value of the force for the determination of K_{IC} was taken at the point on the force/clip gauge displacement record corresponding to 5% secant off-set or at maximum load where appropriate. The 5% secant off-set criterion which has been applied to the 'C'-shaped specimen has been shown by Gross and Srawl (1976), Mukherjee (1976) and Kendall et al. (1975) to correspond to a 2% increase in crack length consistent with that generally accepted for the standard compact tension specimen.

The quenched-and-tempered specimens were fatigue pre-cracked and tested to ASTM E399 using a servo-hydraulic test system. All tests were conducted at 21°C.

After testing, tensile specimens were machined from the specimens and used for the measurement of 0.2% proof stress, UTS and elongation.

4. RESULTS

Hardness measurements, taken across a section corresponding to the fracture plane of the specimens, showed that the specimens were of uniform hardness (after tempering) through the wall thickness (~ 25 mm).

4.1 Fracture Toughness

For the range of yield strength states investigated, the 'C'-shaped specimens behaved in a manner typical of standard compact tension fracture toughness specimens. Those specimens with yield strength states 1270 MPa and above exhibited little deviation from linear-elasticity with rapid failure occurring at the maximum load. Those of lower yield strength states exhibited Type I force-displacement records which were generally invalid using criteria outlined in ASTM E399.

The fracture toughness and tensile data are summarized in Table III.

* British Iron and Steel Research Association Report MG/E/308/67.

5. DISCUSSION

5.1 The 'C'-Shaped Specimen

This work has demonstrated that useful 'C'-shaped specimens of a standard geometry can be taken from a large calibre projectile such as the 5"/54 Naval Projectile. It appears feasible to take similar specimens, conforming to the geometries proposed by Underwood et al. (1974, 1976), from 105 mm and 155 mm projectiles, see Appendix I. However, unlike the case of specimens cut from gun tubes, the greatest limitation of the 'C'-shaped specimen taken from artillery projectiles is that it is not particularly economic with respect to material and preparation time. Because of the shape of the artillery projectile (generally) it is possible to machine only a limited number of large-width specimens, W , (for valid K_{IC} data) and this may mean that a projectile in which the driving band seat has been machined cannot be sectioned and tested. The testing of projectiles from a production line may therefore involve the removal of test projectiles prior to the final machining operations.

The production of the 'C'-shaped specimen from an artillery projectile is a relatively simple but time consuming procedure and involves the turning of the inner and outer radii, surface grinding of the two side faces, notching and the drilling of the pin-holes. The tolerances specified in ASTM E399 (1978) can usually be met, however, experience has shown that there may be a slight movement in the specimens if they are initially machined as annuli which are then cut into two specimens. Thus it may prove necessary to place the pin-holes in the specimens after they have been cut from the annuli.

A major limitation of the 'C'-shaped specimen from an artillery projectile is that it will give a measurement of fracture toughness in one orientation only. However, this orientation is possibly the least tough orientation in an artillery projectile and so the specimen should produce relevant results. The 'C'-shaped specimen allows the measurement of toughness in the radial direction and hence is simulative of a longitudinal crack in the projectile wall with the loading in the hoop direction which arises from the set-back and spin-up of the projectile on launching. Should the measurement of the fracture toughness in other orientations prove to be necessary then other specimen configurations must be used. Geometric restrictions may therefore dictate the need to develop suitable miniature fracture toughness specimens* which may involve less extensive preparation than the 'C'-shaped specimen.

* Work is in hand in these laboratories to investigate the suitability of pre-cracked charpy specimen for the fracture toughness studies of artillery projectiles, Saunders (1981).

5.2 Fracture Toughness

The fracture toughness data presented in Table III were largely as expected from the heat treatments given to the high manganese steel used. The metallography and fractography of this steel are described in detail by Saunders (1981). For the purpose of this Report it is sufficient to note that the heat treatments produced fracture behaviour ranging from intergranular fracture at high hardness, due to temper embrittlement, to fully dimpled rupture at the lowest hardness condition with a mixture of these two fracture modes at the intermediate hardness levels.

The yield strength states used in this work were higher than those usually specified for the new-generation high fragmentation steels and hence the estimates of critical specimen dimensions (viz, crack length and thickness greater than $2.5 (K_{IC}/\sigma_{0.2})^2$) are slightly low. They show that, for valid K_{IC} data, specimens taken from high fragmentation shells will need to have dimensions similar to those of the specimens used in these tests, although it is possible that with some projectiles the ASTM dimension criteria may not be met. (Compare the dimensions calculated in Table III with those of specimens from projectiles given in Appendix I).

6. CONCLUSIONS

6.1 The 'C'-shaped specimen appears to be suitable for the measurement of the through-wall toughness of large-calibre artillery projectiles manufactured from high fragmentation steels.

6.2 The use of the 'C'-shaped specimen for fracture toughness testing does not appear to require any significant changes in the standard K_{IC} determination test procedure.

6.3 The specimen gives a simple and representative test method for studying those factors which influence the toughness of artillery projectiles.

6.4 The steel used for this work can be heat treated to cover a wide range of yield strength states and fracture toughness conditions and hence appears to be a suitable material for the study of the relationships between fragmentation behaviour and fracture toughness.

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T A B L E I

STEEL COMPOSITION SPECIFICATION FOR 5"/54

NAVAL PROJECTILE

Element	C	Mn	P	S	Si
min	0.48	0.95	-	0.025	0.15
max	0.55	1.30	0.04	0.05	0.3

T A B L E I I

COMPARISON OF TWO CALIBRATIONS FOR 'C'-SHAPED SPECIMENS

WITH $X/W = 0.5$

(KB $\sqrt{W/P}$ values)

a/W	Underwood and Kendall (1974) $r_3 = (r_2 - .4W)$		Underwood and Kendall (1978) $r_3 = (r_2 - .25W)$	
.45	12.9740	5" C	12.9658	5" C
.50	15.1442	"	15.1788	"
.55	17.9466	"	18.0083	"
.45	12.8280	155 mm C	12.8810	155 mm C
.50	14.9738	"	15.0902	"
.55	17.7446	"	17.9154	"

TABLE III

FRACTURE TOUGHNESS DATA FOR 'C'-SHAPED SPECIMENS IN A
RANGE OF YIELD STRENGTH, $\sigma_{0.2}$, STATES
TESTS AT 21°C

Tempering Temp, °C	300	350	400	470	510
$\sigma_{0.2}$, MPa	-	1440	1270	1020	915
σ_{UTS} , MPa	-	1610	1400	1160	1055
σ_{UTS} conv. from hardness ^(a)	1720	1670	1475	1170	1090
HV30	520	505	450	360	335
K_Q , MPa m ^{1/2} on 5% offset	-	-	-	86.5(C-7) ^(b) 77.7(C-8)	90.6(C-9) 87.4(C-10)
K_Q , MPa m ^{1/2} on Pmax	30.1(C-1) ^(b) 28.0(C-2)	32.4(C-3) 26.6(C-4) ^(c)	57.3(C-5) 50.4(C-6)	94.0(C-7) 90.6(C-8)	101.2(C-9) 98.4(C-10)
Force Displacement Record	C-1 TYPE I	C-3 TYPE III	C-5 TYPE I	C-7 TYPE I	C-9 TYPE I
	C-2 TYPE III	C-4 No record ^(c)	C-6 TYPE III	C-8 TYPE I	C-10 TYPE I
$2.5 \left(\frac{K_Q}{\sigma_{0.2}} \right)^2$, mm ^(d)	- -	1.3(C-3) .9(C-5)	5.1(C-5) 3.9(C-6)	17.8(C-7) 14.5(C-8)	24.5(C-9) 22.8(C-10)
Valid/Invalid ^(e)	C-1 Valid; K_{Ic}	C-3 Invalid	C-5 Valid; K_{Ic}	C-7 Invalid	C-9 Invalid
	C-2 Invalid	C-4 Invalid	C-6 Valid; K_{Ic}	C-8 Invalid	C-10 Invalid

(a) tensile tests were not conducted on the material tempered at 300°C; the conversion from hardness gives an approximate UTS, A.S.M. Metals Handbook, 8th Edition, p.1234.

(b) specimen number

(c) broke during fatigue pre-cracking, Pmax recorded.

(d) calculation of specimen dimensions, B and a, for test validity.

(e) ASTM criteria such as fatigue pre-cracking and crack length ($a_i + a_{fatigue}$).

APPENDIX I

Approximate Dimensions of 'C'-Shaped Specimens from Fragmenting Projectiles

Dimensions in mm

Critical Dimensions		r_1	r_2	$W=(r_1-r_2)$	^B (ASTM recommendation)
5"/54	(127 mm)	39.0	62.75	23.75	11.8
L15A1	(155 mm)	55.0	77.0	22.0	11.0
M549	(155 mm)	64.5	77.0	12.5	6.25
XM795	(155 mm)	possibly similar dimensions to M549			
M107	(155 mm)	49.0	77.0	28.0	14.0
M1	(105 mm)	33.0	52.0	19.0	9.5

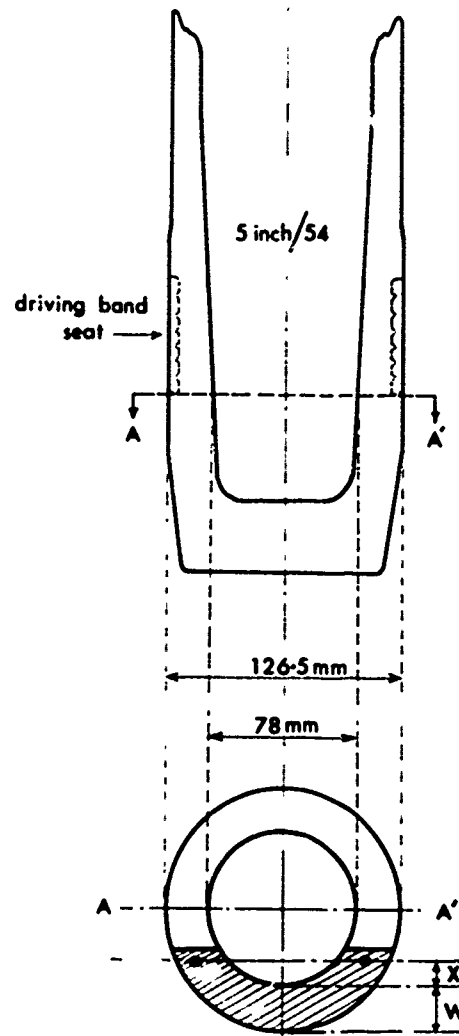


FIG. 1(a) A 'C'-shaped specimen taken from the 5"/54 projectile, with $X/W = 0.5$ and the ring width the maximum possible.

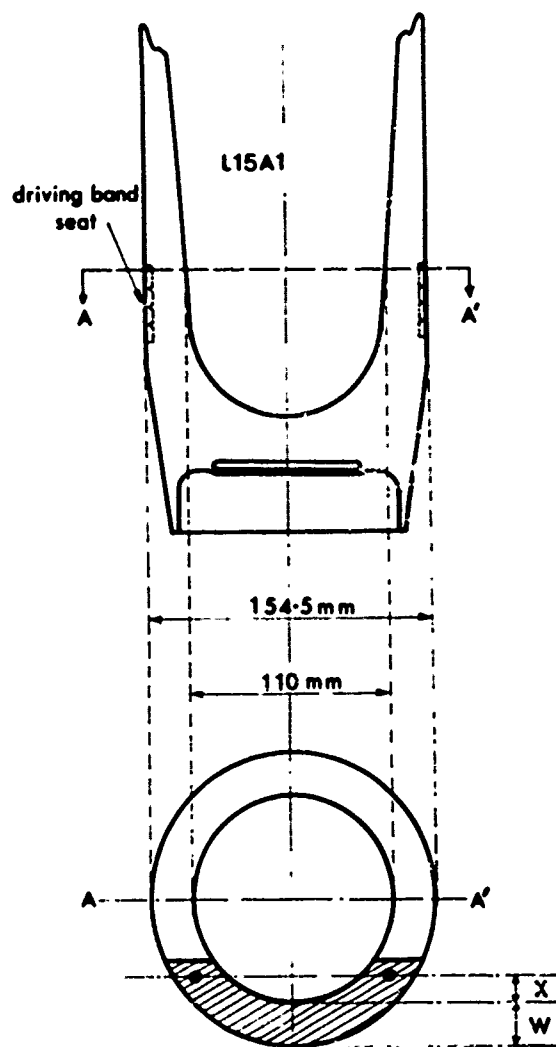


FIG. 1(b) A 'C'-shaped specimen taken from the L15A1 projectile with $X/W = 0.5$. Projectiles in which the driving band seats have not been machined permit the largest possible ring width.

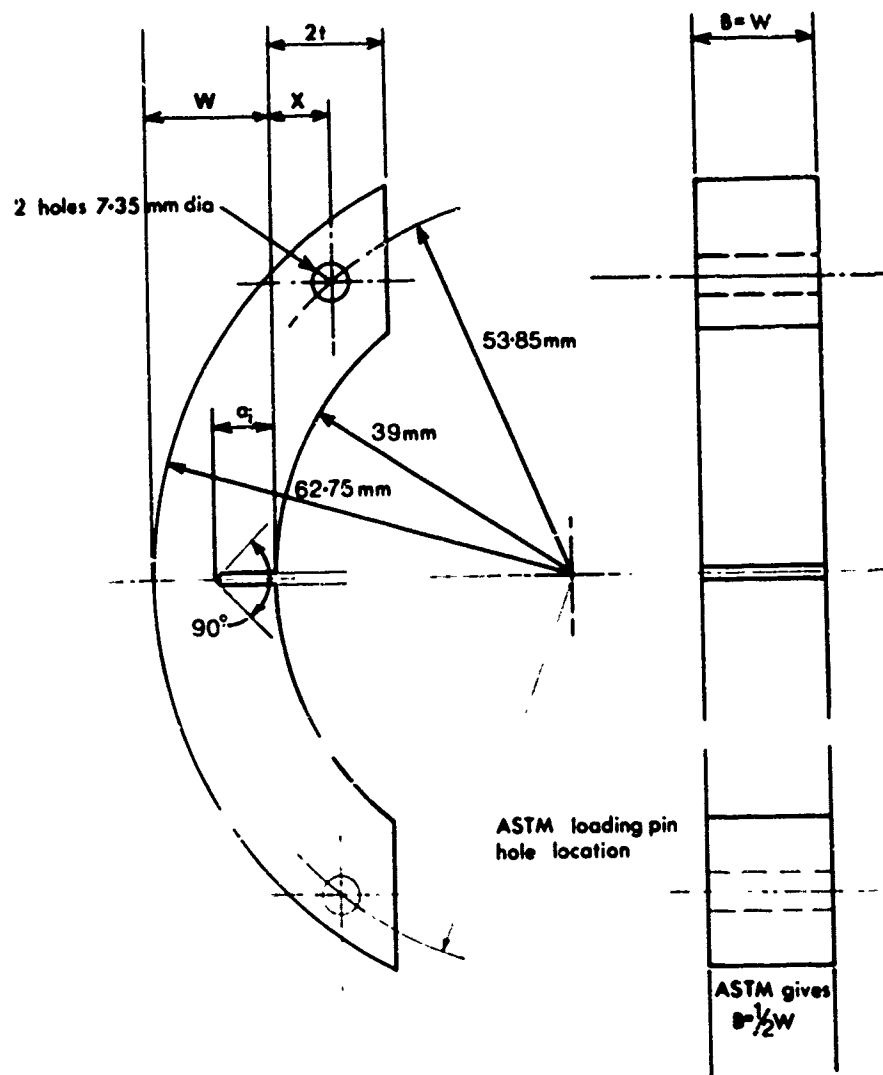


FIG. 2 The 'C'-shaped specimen from the 5"/54 projectile. The ASTM loading pin hole location is also shown on the diagram.

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