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RESPONSE OF SMA AND NARROW GAP HY80 WELDMENTS TO EXPLOSIVE SHOCK LOADING

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ABSTRACT

The performance of high yield strength steel plate and weldments, subjected to high levels of dynamic plastic deformation from explosive shock, is an important aspect in the study of materials used in submarine pressure hull construction. This report describes the development of an explosive shock test procedure and its application to study the behaviour of HY80 plate, several shielded metal arc weldments of HY80, and several metal inert gas narrow gap HY80 weldments.

E9018M shielded metal arc weldments and 70S1 and 100S1 narrow gap weldments survived numerous shock loadings without crack development, with a total thickness reduction in excess of 16% near the center of the panels. Minor cracking developed in E11018M weldments and complete plate brittle fracture occurred in the E7018 weldment at lower levels of plate plastic deformation. Metallurgical investigations revealed the presence of abnormal microstructural components in these weldments which caused the premature crack development in the E11018M weldment and contributed, along with the presence of slag and porosity and weld metal strain concentration, to the complete fracture of the E7018 weldment.

RÉSUMÉ

Le comportement des tôles et des structures soudées en acier à haute ténacité soumises à de fortes déformations plastiques sous l'effet d'ondes de choc explosif constitue un aspect important de l'étude des matériaux utilisés pour la construction des coques intérieures de sous-marins. Le présent rapport décrit la mise au point d'une procédure d'essai aux ondes de choc et son application à l'étude du comportement des tôles HY80, de plusieurs structures HY80 soudées à l'électrode enrobée, et de plusieurs structures HY80 soudées sous gaz inerte selon la technique de faible écartement du joint.

Les structures E9018M soudées à l'électrode enrobée et les structures 70S1 et 100S1 réalisées selon la technique de faible écartement du joint ont supporté de nombreuses ondes de choc sans amorce de fissuration, cela tout en permettant une réduction d'épaisseur totale de plus de 16% près du centre du panneau. Les structures soudées E11018M se sont légèrement fissurées; quant aux structures E7018, des ruptures fragiles complètes se sont développées à des niveaux de déformation plastique inférieurs. L'étude d'échantillons de ces structures a révélé la présence, dans la microstructure, de composants anormaux qui ont provoqué la fissuration prématurée dans les structures E11018M et contribué, avec les scories, la porosité et la concentration de contraintes dans la soudure, à la rupture complète de la structure soudée E7018.

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1.0 INTRODUCTION

An integral part of the submarine materials technology program at Defence Research Establishment Atlantic's Dockyard Laboratory (DREA/DL) is the evaluation of submarine pressure hull weldment response to explosive shock. The ability of the weldment structure to withstand significant plastic deformation prior to the formation and propagation of a crack is an important requirement for modern submarine steels and weldments.

The standard explosion bulge test[1], conceived over 25 years ago at the US Naval Research Laboratory, is recognized as a required qualification test for welding electrodes and welding procedures used in submarine pressure hull construction. Modified versions of this procedure have seen considerable usage in the investigation of factors that determine weldment performance[2,3] as it permits full scale evaluation of the weld metal, fusion zone, heat affected zone and base metal as a complete unit.

This report describes the development and application of a Canadian test procedure to study the nature of dynamic plastic deformation in experimental weldments, to study the mechanisms of failure, to identify areas of weakness across the weldment profile and to relate metallurgical information to the mode of failure. Evaluations of 2.54 cm (1 inch) thick HY80 base plate, shielded metal arc (SMA) weldments of HY80, and narrow gap metal inert gas (MIG) weldments of HY80 were conducted. Five SMA weldments fabricated with various electrodes were explosively tested to compare the shock resistance of undermatched, matched and overmatched weldments. Similarly two different electrodes were employed in the narrow gap weldments.

2.0 EXPERIMENTAL PROCEDURE

2.1 Weldment Preparation

The SMA weldments for this study were prepared by the Ship Repair Unit Atlantic (SRUA) Welding Department in accordance with approved welding procedures for use on OBERON Class Submarines[4]. Electrodes were 0.32 cm (1/8 inch) in diameter. Heat input was approximately 15000 J/cm and a preheat of 121° - 135 °C (250° - 275 °F) was employed. The edge preparation was a 70° double vee groove. The electrodes used were:

E11018M	Atom Arc T	Canadian Liquid Air
E9018M	Atom Arc T	Canadian Liquid Air
E7018	Atom Arc T	Canadian Liquid Air

The narrow gap MIG weldments were prepared by Techno Scientific Inc., Toronto. The gap was 1.27 cm (1/2 inch) and a thin metal plate was used as a backup plate to start the weldment. The wires used were 70S1 and 100S1. The gas employed in this welding process was patented (designated TIME 1 or TIME 2 gas). The chemical compositions and mechanical properties of the materials used are listed in Table 1.

The weldments were ground off to conform to pressure hull fabrication practice. They were then radiographed using an Iridium 192 radioisotope source to ensure that significant defects were not present, which could severely alter the response of the panels to explosive loading.

2.2 Modified Explosion Bulge Procedure

In the explosion bulge evaluation of 2.54 cm (1 inch) thick HY80 plate and weldments, a 61 cm (2 ft) square test panel is subjected to an explosive uniform pressure while supported on a die containing a 38 cm (15 inch) diameter circular hole, as shown in Figure 1. The pressure caused by the explosive charge results in balanced biaxial loading in the bulge apex region and controlled deformation over the unsupported region. The panels are subjected to multiple loadings, each of which is designed to result in a 3% strain and thickness reduction. Although the use of a single large explosive charge would facilitate the evaluation, the use of smaller multiple shock loadings allows a precise rupture strain determination and a clearer delineation of weldment weak spots.

At the center of each experimental panel, 2.54 cm (1 inch) on either side of the weld centerline, points were marked at which plate thicknesses were to be measured (Figure 2). Prior to mounting the panels on the die, a thickness measurement was taken at each location. These measurements were taken with an ultrasonic device which was calibrated to within 0.0025 cm (0.001 inch) prior to each reading.

After the test panel was placed on the die, the explosive charge was suspended above the center of the panel at the appropriate distance. The panels were monitored with thermocouples to ensure that the temperature at the time of firing was -5° C (23°F). As the ambient temperature during the trial was considerably lower than -5°C (23°F), the panels were stored at a slightly warmer temperature to allow for panel cool-down during handling.

Following each shot, the panels were returned to the storage trailer at which time ultrasonic thickness measurements were made at the marked points and the panel depth of bulge recorded. If the panel had not attained the required 16% reduction in thickness and had not developed major cracking extending into the hold down region (the region of the test panel in contact with the die), the panel was then allowed to cool down in preparation for another shot.

2.3 Determination of Standoff Distance

In the explosion bulge test the present recommended charge is 3.18 kg (7 lbs) of pentolite [5]. However as this explosive was not readily available, Composition B was substituted for the DREA trials. This explosive is reported to have approximately 5% more energy per pound than the pentolite and was considered equivalent. Due to the size of the forming molds available, the charge weight was increased to 3.75 kg (8.25 lbs). As a result of these modifications in explosive type and weight, it was evident that a slight increase in standoff distance (the distance between the charge and panel surface), would be required to maintain the 3% panel thickness reduction per shot. An estimate of the adjusted distance was made utilizing the Hopkinson scaling factor for blast waves [6]. Equation 1 was used to estimate the required standoff distance in order to obtain similar shock waves striking a plate surface:

$$R_2 = R_1 \ (W_2/W_1)^{1/3} \qquad (1)$$

in which: R_1 is the original standoff (38 cm) (15 inches)
R_2 is the adjusted standoff
W_1 is the original charge weight (3.18 kg) (7 lbs)
W_2 is the new charge weight (3.75 kg) (8.25 lbs)

The required standoff distance for the new charge was determined to be approximately 40.6 cm (16 inches). To verify the correct distance, a series of unwelded HY80 panels were shock loaded with the charges set at various standoff distances. Table 2 summarizes the experimental findings which show 40.6 cm (16 inches) to be the correct standoff distance to obtain the required approximate 3% thickness reduction per shot. It was decided to use this standoff distance in all future shots with this charge. Table 2 also demonstrates that there exists a large variance in plate response even when similar charges are used at the same standoff distance as seen in panels B4 and B5.

3.0 RESULTS

3.1 Explosive Response of Unwelded HY80 Panels

Two unwelded HY80 panels were first subjected to numerous loadings to define the deformation history per shot of the HY80 steel. Table 3 shows the accumulated percentage thickness reduction. An accumulated percentage thickness reduction of 21% following 9 shots was attained without the initation of a crack.

3.2 Explosive Response of SMA HY80 Weldments

Table 4 tabulates the values of accumulated percentage thickness reduction for each of the five shock tested shielded metal arc weldments evaluated.

The E7018 weldment fractured completely (Figure 3) during the fifth shot with an accumulated thickness reduction in the adjacent parent plate, prior to the last shot, of only 5%. Both E9018M weldments sustained eight loadings without crack initiation as shown in Figure 4. The E11018M weldments developed cracks after small levels of bulging (Figure 5). The cracking (Figure 6) began across the weld at the bulge apex and tended to turn parallel to the weld direction upon reaching the heat affected zone. The cracks did not extend into the supported region of the panels.

3.3 Explosive Response of Narrow Gap Weldments

Three narrow gap weldments were evaluated to establish their ability to withstand shock loading and for comparison with the SMA weldments. Table 5 summarizes their responses.

Both 100S1 narrow gap weldments sustained eight shock loadings without the formation of a crack (Figure 7). The average total accumulated thickness reduction was 17%. The 70S1 narrow gap weldment experienced six loadings without cracking and attained 14% thickness reduction.

3.4 Microstructural Analysis

The microstructure shown in Figure 8 was typical for the E7018 weldment tested. The microstructure had approximately ten percent acicular ferrite, with the predominant constituent being very coarse polygonal proeutectoid ferrite. This microstructure is not what should normally be found and is typical of slow weld cooling rates, associated with high preheating temperatures or excessive heat input, and is characterized by generally low toughness[7]. It should be noted that the dynamic toughness of the E7018 weldments was somewhat less than that of the other weldments[8].

The microstructures of the E9018M weldments, as seen in Figure 9, were approximately eighty percent acicular ferrite. There was also a small amount of polygonal proeutectoid ferrite present. This type of microstructure is almost ideal as it contains a finer acicular ferrite structure with none of the polygonal proeutectoid ferrite networks.

The microstructure in the E11018M weldments was predominantly fine acicular ferrite as shown in Figure 10. However, near the top portions (final passes) of the weldment, the microstructure revealed a fine intercrystalline phase (proeutectoid ferrite) along the prior austenitic grain boundaries[7] (Figure 11). In the upper center portions of the weldment, there appeared to be an alignment to the ferrite structure within these grains which is indicative of a bainitic microstructural component which is detrimential to weldment toughness. These microstructural components are not generally present and are the result of excessive heat input.

As seen in Figure 12, the narrow gap 70S1 weldment revealed only about fifty percent coarse acicular ferrite with gross amounts of polygonal ferrite with sideplate ferrite growth. These microstructural components can adversely affect the weldment's toughness.

The narrow gap 100S1 weldments (Figure 13) displayed a predominantly fine acicular ferrite microstructure with a minimum amount of polygonal proeutectoid ferrite. This microstructure is most desirable as it will exhibit good toughness properties.

Based on the above microstructural observations, the most desirable weldment properties are contained in the E9018M and the 100S1 test panels. The effects of polygonal proeutectoid ferrites and the bainitic microstructure, such as seen in the E7018, E11018M and the 70S1 weldments are not desirable.

3.5 Fractographic Analysis

The E7018 welded panel fractured completely along the length of its weldment (Figure 3) on the fifth shot. The fracture initiated just off center of the apex of the bulge and displayed a classic chevron pattern of fracture, as seen in Figure 14. Fractographic analysis in the scanning electron microscope showed that the mode of fracture in the initiation region was cleavage (Figure 15). Slag and porosity evident in the fractograph are felt to have been the initiating sites for the fracture. The fact that the fracture surface displayed a mainly cleavage fracture overall, with small amounts of dimple rupture (Figure 16), indicated that this weldment had poor toughness. Had the slag and porosity not been present, it is likely that the fracture would have initiated at the apex of the bulge.

Both E11018M weldments cracked at the apex of the bulge, in the center of the weld, on the fifth shot. The cracks ran across the weldment and into the parent plate (Figure 6). The initiation point of this crack was in the top center portion of the weld and the crack propagated down and outwards towards the bottom of the weld (Figure 17). The initiation point, viewed under the scanning electron microscope, showed an intergranular fracture mode (Figure 18). As the crack propagated down into the weld metal, the fracture mode changed to cleavage and then to almost fully dimple rupture (Figure 19). This weldment exhibited fair toughness in all but the top portion where crack initiation occurred.

4.0 DISCUSSION

The purpose of the standard explosion bulge test as defined in Reference 4 is to determine whether experimental weldments can be explosively deformed to a predetermined level prior to panel failure. Failure is defined by the presence of major cracking which has extended into the hold-down region of the plate or by the shedding of fragments from the test plate during loading. For HY80 panels the predetermined deformation level is defined by a minimum 16% thickness reduction at the bulge apex[9].

When comparing thinning levels attained in the welded panels surviving the highest levels of loading (eight shots), the matching E9018M SMA and 100S1 narrow gap weldments responded similarly to the unwelded HY80 panels. As well, the level of bulging after eight shots for both weldments was similar to the unwelded panel as seen in Table 6.

In the E7018 SMA weldment it was noted after four shots that the thickness reductions, as measured in the parent plate near the weld, were approximately half those of the unwelded HY80 panel after four shots. Necking and elongation of the lower yield strength weld metal, indicative of higher plastic strain levels in the weld material was observed. This would account for the lower level of plastic strain in the parent metal. Although the weldment successfully passed the pretest NDT inspection, the presence of small amounts of slag and porosity caused initiation of a crack in an area other than the apex of the bulge. The panel fractured completely as a result of the presence of an abnormal microstructure probably caused by slow cooling rates in the weldment due to either excessive heat input or too high an interpass temperature, in combination with the high strain energy concentration in the lower strength weld metal. The presence of slag or porosity also contributed to the premature crack initiation.

After four loadings, the overmatched E11018M weldment displayed similar thickness reduction levels as the unwelded HY80 panels, but less bulging. However, for equivalent levels of bulging, the strain levels measured in the parent metal adjacent to the weldment were higher than in the unwelded HY80 panel as shown in Figure 20. This was due to the higher flow strength in the weld metal, compared to the flow strength of the base metal, causing a strain deconcentration in the transweld direction[10] and resulting higher level of stretching in the adjacent parent plate at the point of thickness measurement. The cracking initiated in areas where a fine intercrystalline ferrite phase and a bainitic microstructure were present as a result of excessive heat input during welding. Had the predominately acicular ferrite microstructure been present in the final passes of this weld, the cracking would not likely have initiated until higher levels of deformation were attained. The presence of a ductile failure mode as the crack passed into the acicular ferrite microstructure of the lower weld bead passes, points to a much greater toughness in this area.

The undermatched 70S1 narrow gap weldment displayed slightly more parent metal thinning and slightly higher bulging when compared with the unwelded panels after four shots. However when again compared with the unwelded panel, at equivalent levels of bulging (Figure 21), the 70S1 weldment parent metal thickness reductions were lower than the unwelded panel levels. When the 70S1 narrow gap weldment was compared to the E7018 SMA weldment after four shots it was noted that the adjacent parent plate thinning was less in the E7018 SMA panel and also the depth of bulging in the E7018 SMA panel was less. This can be attributed to the variance in available explosive energy between otherwise similar charges. At equivalent levels of deformation, however, the adjacent parent plate thinning levels were comparable. This was expected because the welding electrodes in both cases were of equivalent yield strength.

5.0 CONCLUSIONS

(1) A DREA modified explosion bulge procedure has been developed from the basics of the standard American explosion bulge test, with the aim of studying plate and weldment response and failure under dynamic shock loading.

(2) The dynamic plastic behaviour of shielded metal arc HY80 weldments, narrow gap HY80 weldments and HY80 base plate exposed to repeated explosive shock loading has been studied and the following conclusions have been made:

a. The SMA weldments fabricated with E9018M electrodes, the narrow gap weldments fabricated with 100S1 wire and the HY80 base plate responded similarly to explosive loading and developed an accumulated thickness reduction in excess of 16% prior to crack initiation.

b. Complete fracture of the E7018 weldment occurred at low levels of parent plate thickness reduction as a result of the presence of abnormal microstructural components (polygonal proeutectoid ferrite) in combination with the presence of slag and porosity and the strain energy concentration in the lower strength weld metal. Cracking developed in the E11018M weldments after an average of 7% thickness reduction as a result of fine intercrystalline phases along prior austenitic grain boundaries and a bainitic microstructural component present in the last welding passes in the top portion of the weld. These microstructures which caused the premature cracking should not be considered typical of weldments fabricated with these electrodes.

TABLE 1

CHEMICAL AND MECHANICAL PROPERTIES

MATERIAL		HY80 PLATE	E7018 ROD	E9018M ROD	E11018M ROD	70S1 WIRE	100S1 WIRE
Chemical Composition							
C		.18	.12	.10	.10	.07/.15	.08
Mn		.1/.4	.4/1.25	.6/1.25	1.3/1.8	1.4/1.85	1.25/1.8
Ni		2/3.25	.25	1.4	1.2/2.5	-	1.4/2.1
Cr		1/1.8	.15	.15	.4	-	.3
Mo		.2/.6	.35	.35	.25/.5	-	.25/.55
Mechanical Properties (Nominal)							
σ_y	(MPa)	552	400	539	676	414	606
	(Ksi)	80	58	78	98	60	88
σ_u	(MPa)	655	482	620	758	496	689
	(Ksi)	95	70	90	110	72	100
% Elong.		20	24	24	20	22	16

TIME Gas Chemical Composition

TIME1 - 65% Ar, 26.5% He, 8% CO_2, .5% O_2

TIME2 - 44% Ar, 52% He, 3.8% CO_2, .18% O_2

TABLE 2

STANDOFF DISTANCE DETERMINATION

HY80 PANEL #	STANDOFF DISTANCE (CM.)	SHOT #	% THICKNESS REDUCTION PER SHOT
B1	56	1	1.48
		2	1.59
B2	51	1	1.58
		2	2.09
B3	46	1	2.08
		2	2.02
		3	1.03
B4	40.6	1	3.45
		2	2.75
		3	1.78
B5	40.6	1	2.79
		2	1.33
		3	2.97

TABLE 3

EXPLOSIVE RESPONSE OF UNWELDED HY80 PANELS

	ACCUMULATED PERCENTAGE THICKNESS REDUCTION	
PLATE #	B4	B5
SHOT #		
1	3.5	2.8
2	6.2	4.1
3	7.9	7.0
4	9.0	9.2
5	11.1	*N
6	12.2	-
7	15.3	-
8	18.1	-
9	20.8	-

*N - No Further Shots

TABLE 4

EXPLOSIVE RESPONSE OF SMA WELDMENTS

	ACCUMULATED PERCENTAGE THICKNESS REDUCTION				
PLATE #	C1	C2	C8	C6	C7
WELDING ROD	E7018	E9018M	E9018M	E11018M	E11018M
SHOT #					
1	1.3	2.3	1.6	2.1	1.6
2	2.4	4.3	2.7	4.0	3.7
3	3.8	6.2	4.3	7.2	*C
4	5.0	8.0	6.6	9.6	-
5	*F	9.9	8.2	*C	-
6	-	11.8	11.3	-	-
7	-	13.4	13.6	-	-
8	-	15.9	*N	-	-

*C - Major Cracking
*F - Complete Fracture
*N - No Further Shots

TABLE 5

EXPLOSIVE RESPONSE OF NARROW GAP WELDMENTS OF HY80

	ACCUMULATED PERCENTAGE THICKNESS REDUCTION		
PLATE #	C3	C4	C5
WELDING WIRE	70S1	100S1	100S1
SHOT #			
1	2.9	2.6	3.0
2	5.3	5.5	6.8
3	8.1	7.2	8.8
4	11.3	9.7	9.7
5	13.7	11.0	10.9
6	*N	13.3	12.5
7	-	14.8	15.4
8	-	17.4	17.0

*N - No Further Shots

TABLE 6

DEPTH OF BULGE FOR TEST PANELS

PANEL	DEPTH OF BULGE (cm.)		
	After 4 Shots	After 6 Shots	After 8 Shots
HY80	7.4	8.6	10.1
E7018 SMAW	6.4	-	-
E9018M SMAW	7.4	8.4	9.9
E11018M SMAW	6.4	-	-
70S1 NG	8.6	9.7	-
100S1 NG	7.6	9.1	10.4

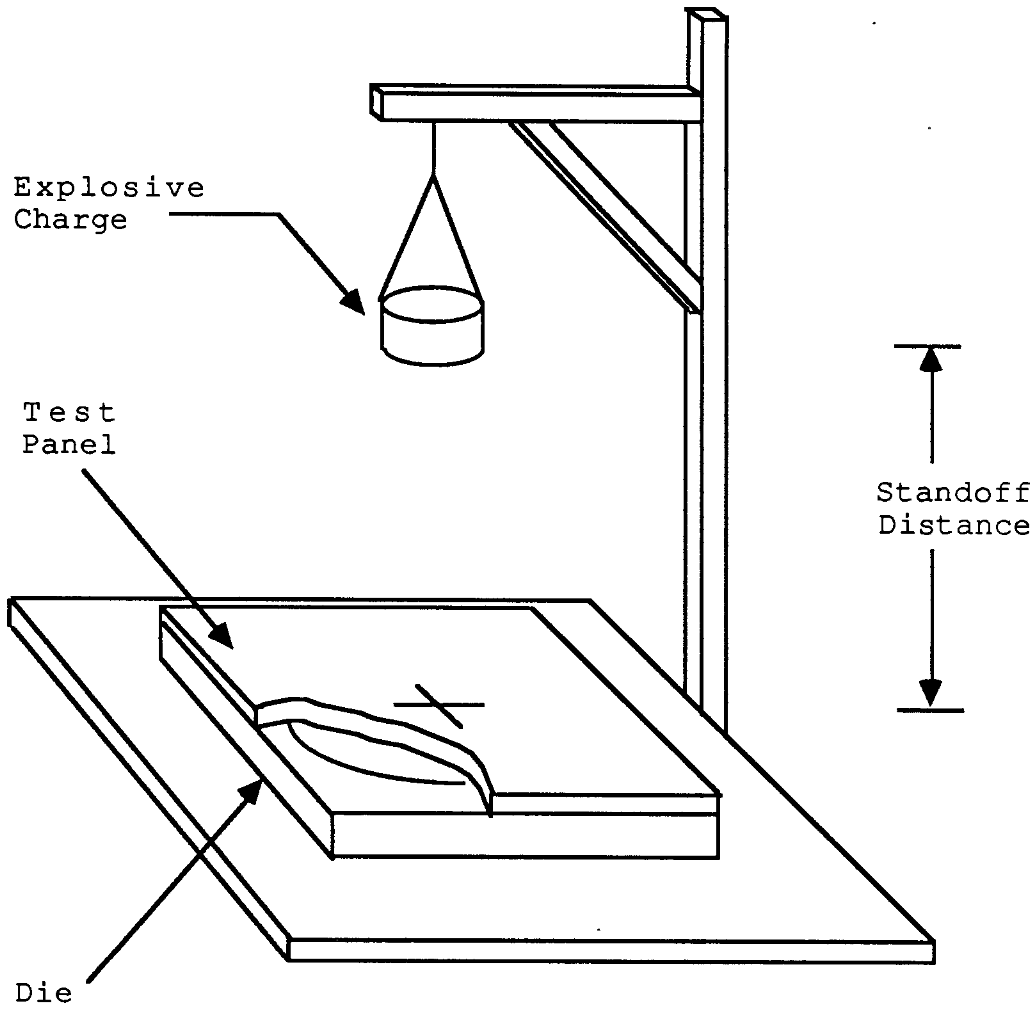
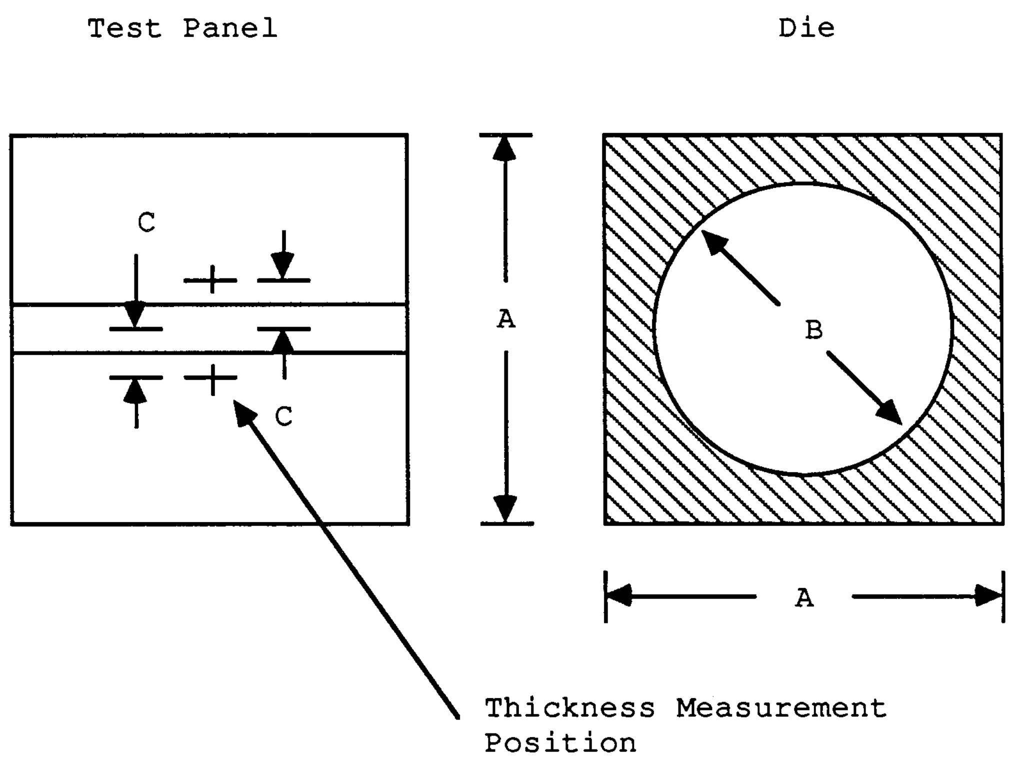


Figure 1: Explosion bulge test set-up



Dimensions (cm.)	Recommended (as per ref. 5)	DREA Version
Panel Size (A)	50.8	61
Bulge Size (B)	38	38
Measurement Position (C)	2.54	2.54
Standoff	38	40.6
Explosive Weight (Kg)	3.18	3.75

Figure 2: Dimensions for Shock Trial (cm.)

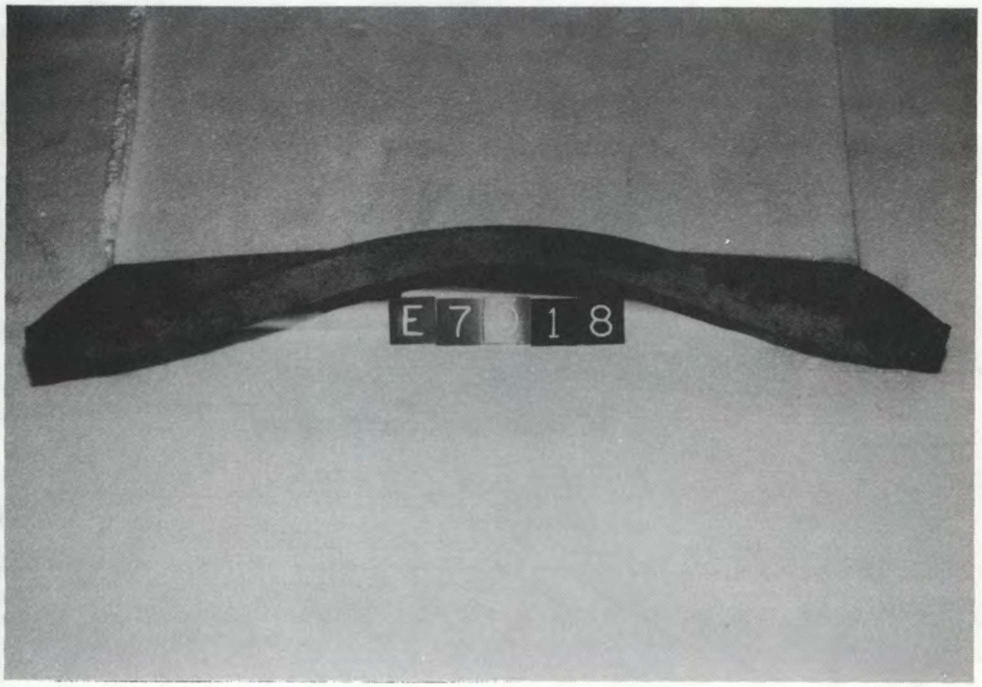


Figure 3: View of completely fractured E7018 test panel

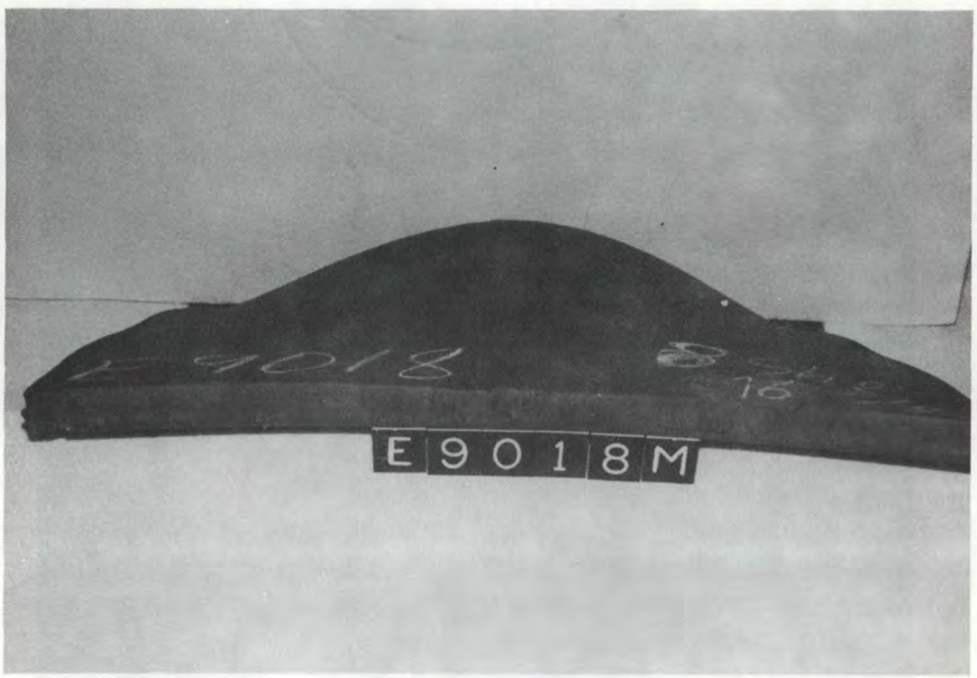


Figure 4: E9018M test panel after eight shots

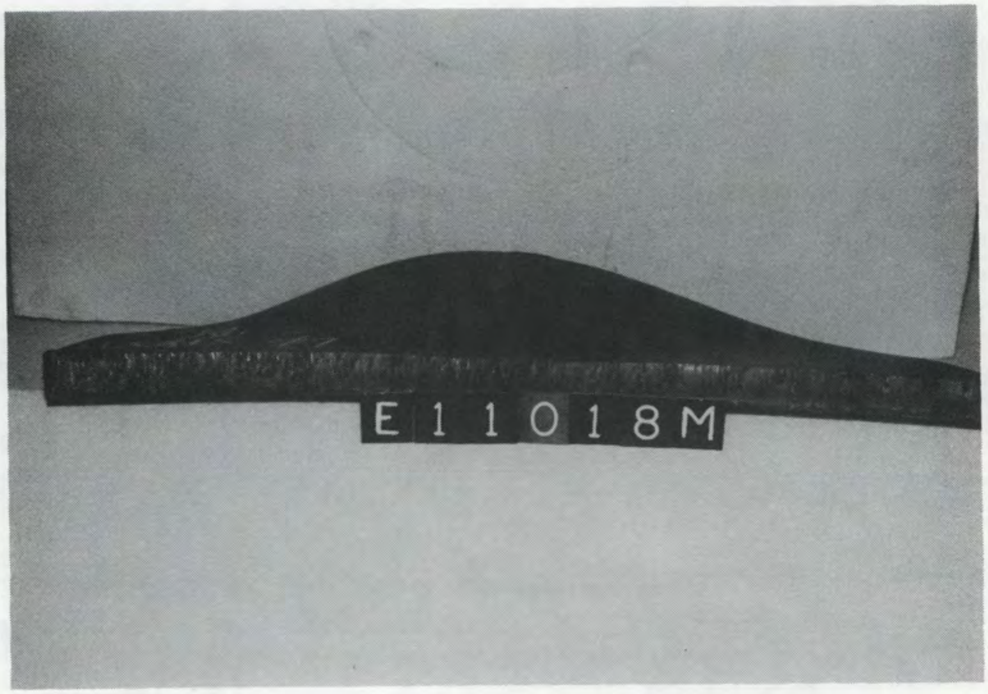


Figure 5: E11018M test panel after three shots

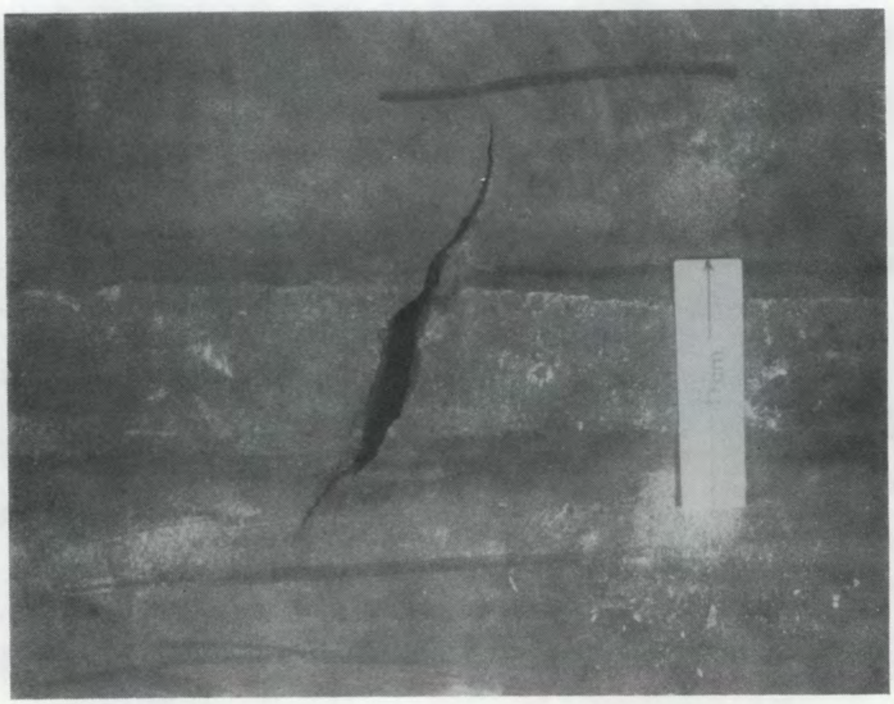


Figure 6: Cracking in E11018M test panel after three shots

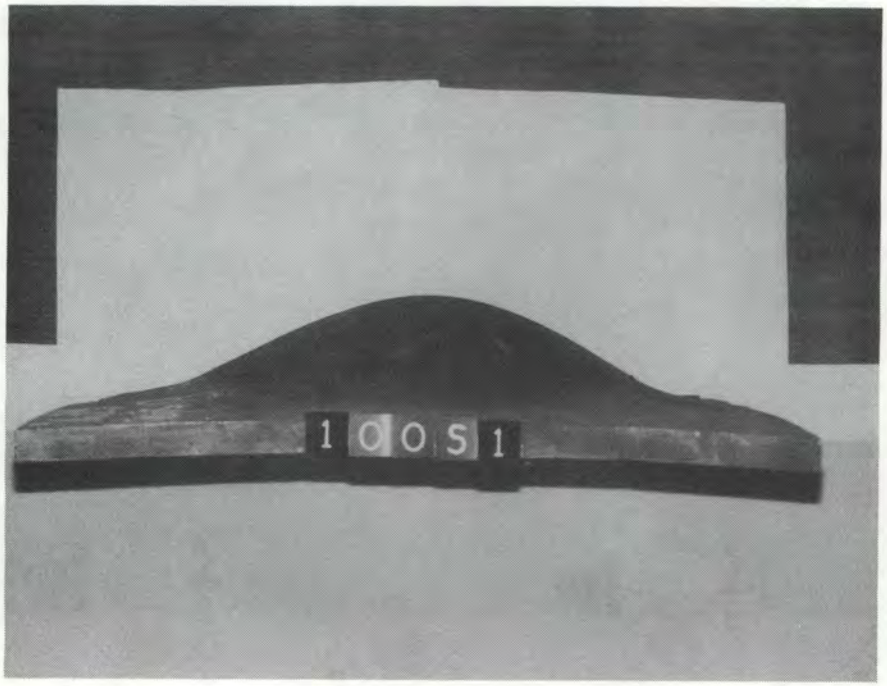


Figure 7: 100S1 narrow gap weldment after eight shots

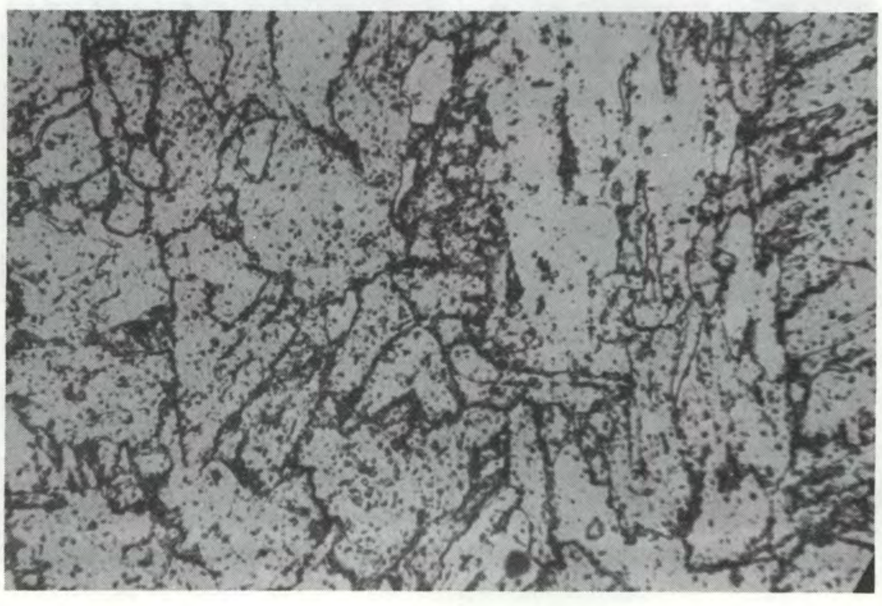


Figure 8: Microstructure of E7018 weld metal showing coarse polygonal proeutectoid ferrite (500X)

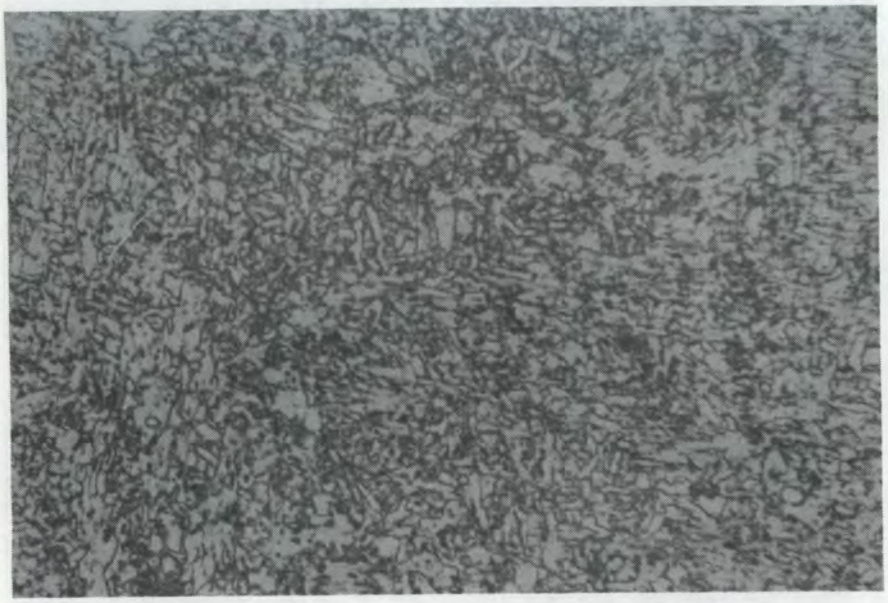


Figure 9: Microstructure of E9018M weld metal showing fine acicular ferrite (500X)

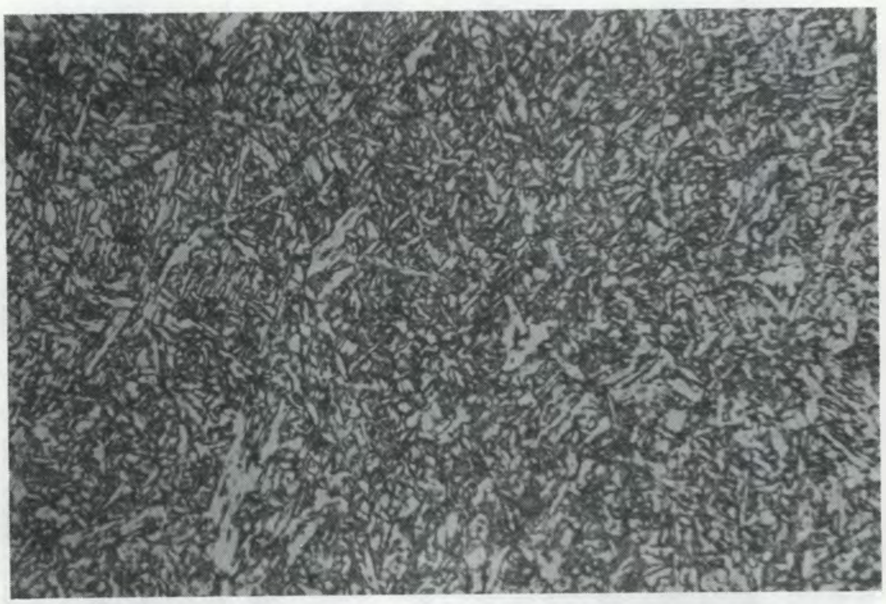


Figure 10: Microstructure of the main body of the E11018M weld metal showing fine acicular ferrite (500X)

Figure 11: Microstructure of final passes in the E11018M weld metal showing intergranular and aligned ferrite (Bainite) (1000X)

Figure 12: Microstructure of 70S1 Narrow Gap weld metal showing coarse acicular ferrite and side plate ferrite (500X)

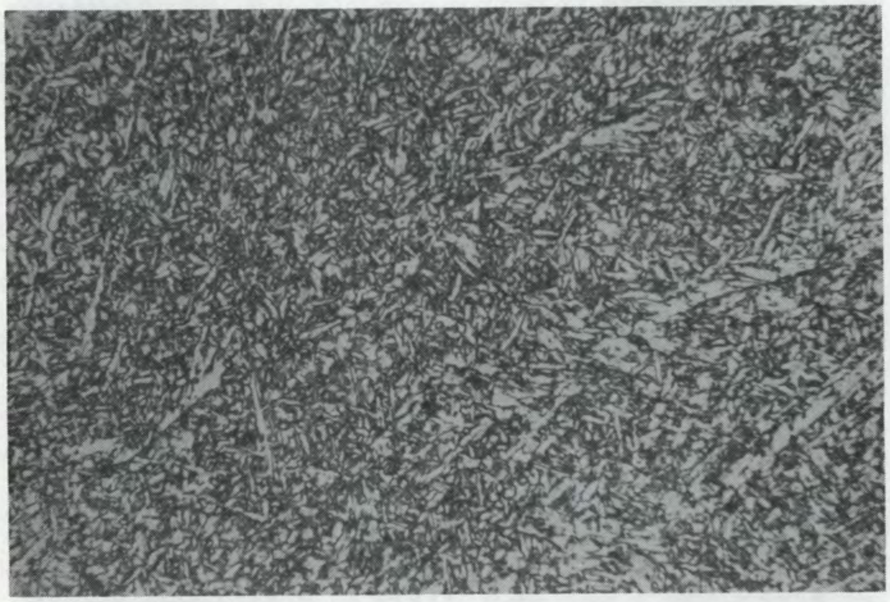


Figure 13: Microstructure of 100S1 Narrow Gap weld metal showing fine acicular ferrite (500X)

Figure 14: Fracture surface of E7018 weld showing chevron fracture pattern

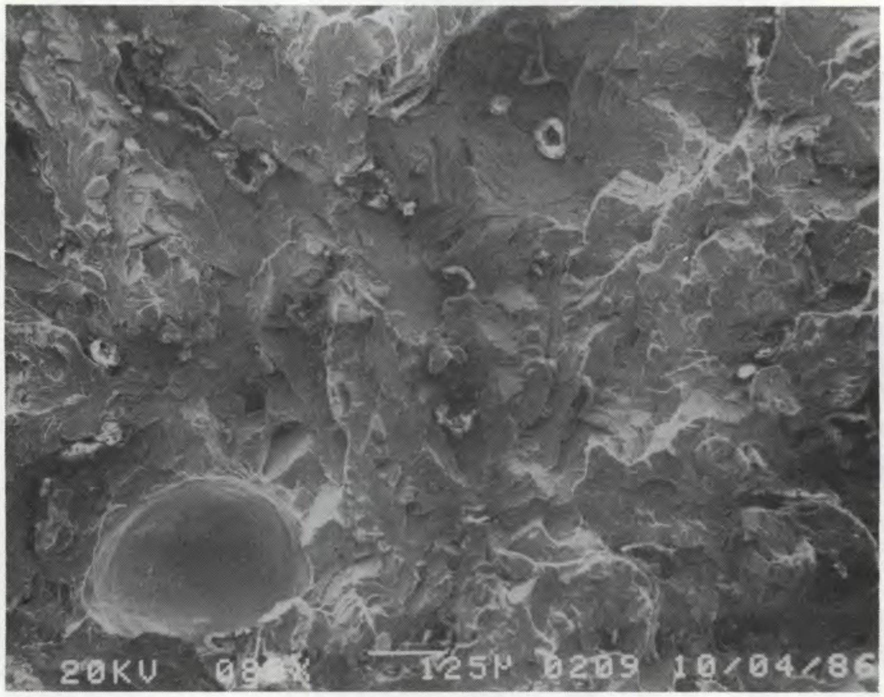


Figure 15: Fractograph of crack initiation point of E7018 weld showing slag, porosity and cleavage fracture (80X)

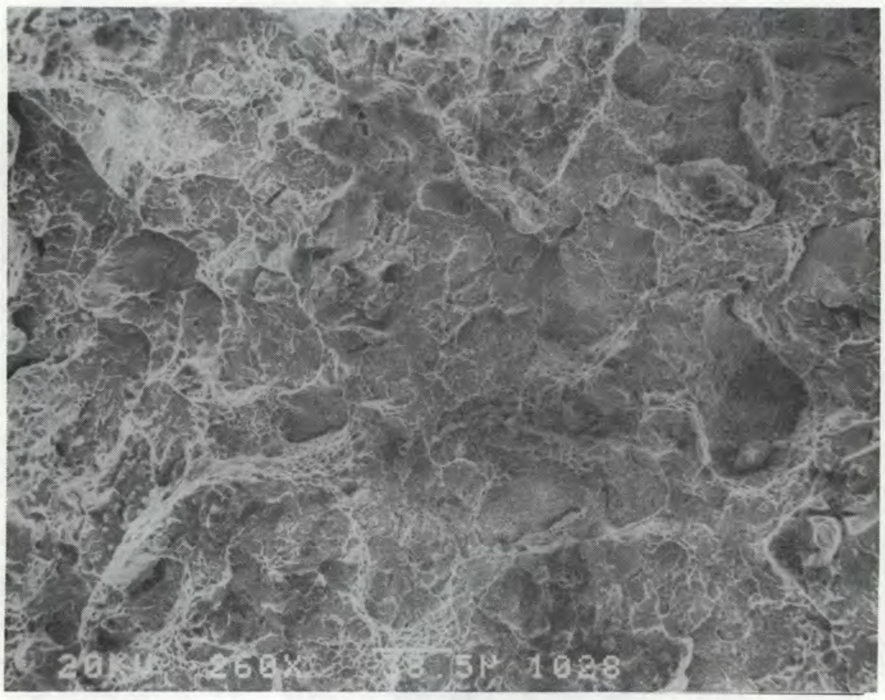


Figure 16: Fractograph of general fracture surface in E7018 remote from initiation point showing mixed cleavage and dimple fracture (260X)

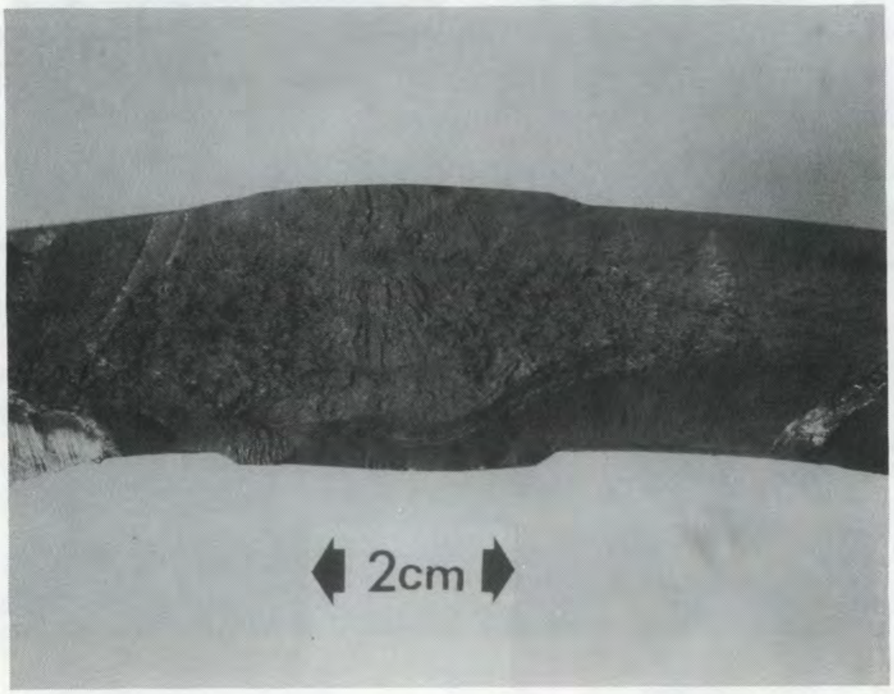


Figure 17: Fracture surface of E11018M weld

Figure 18: Fractograph of crack initiation point in E11018M weld showing intergranular fracture (179X)

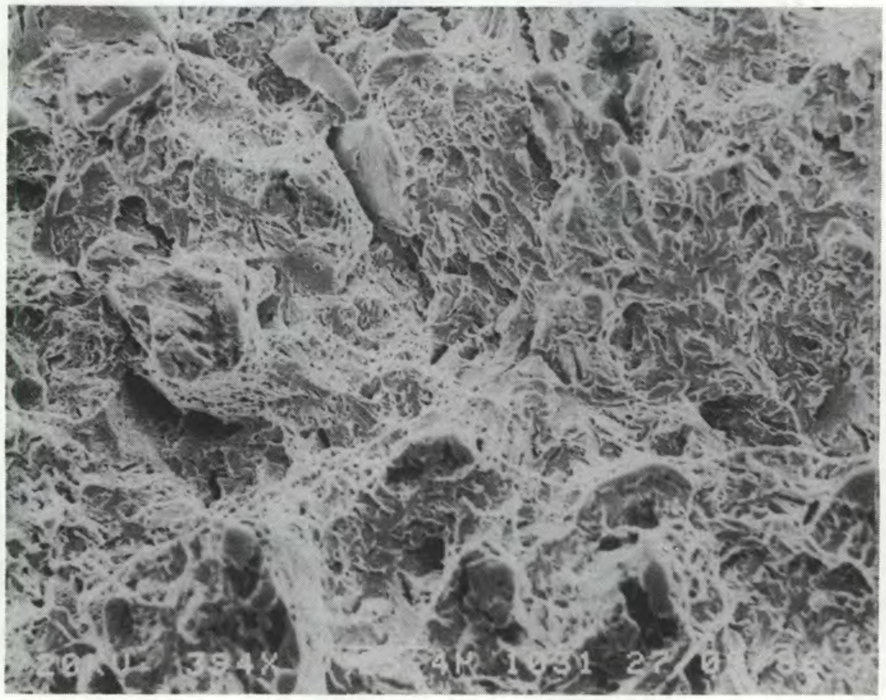


Figure 19: Fractograph of E11018 weld remote from initiation point showing fully dimpled rupture (394X)

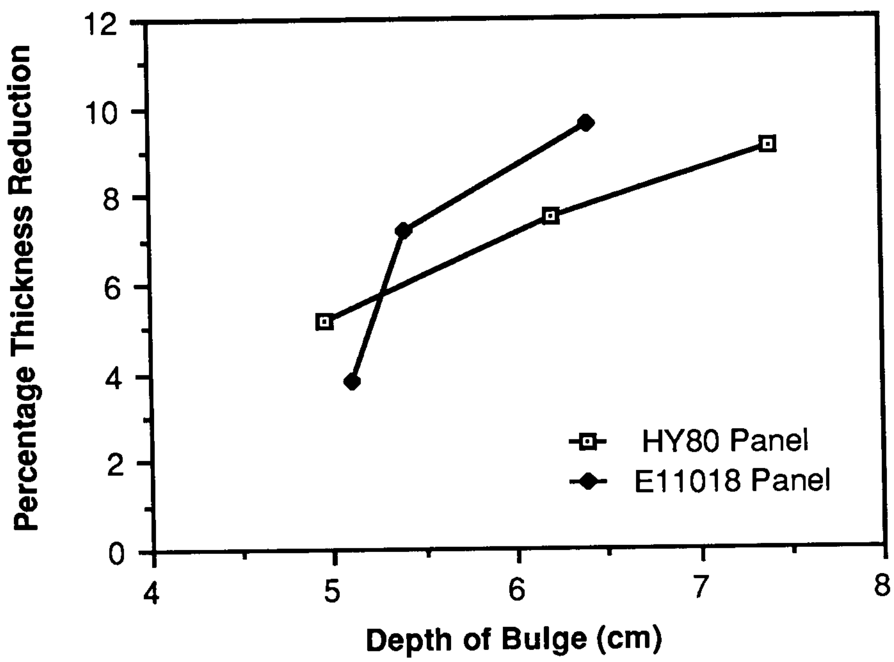


Figure 20: Panel Thickness Reductions Versus Depth of Bulging For HY80 Panel and E11018 Panel

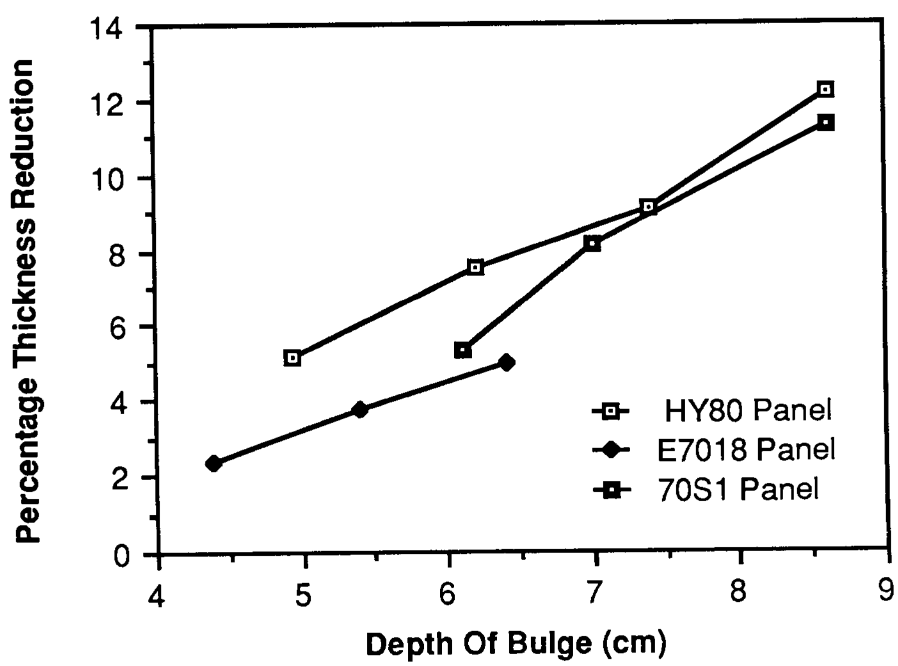


Figure 21: Panel Thickness Reductions Versus Depth of Bulging For HY80, 70S1 and E7018 Panels

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The performance of high yield strength steel plate and weldments, subjected to high levels of dynamic plastic deformation from explosive shock, is an important aspect in the study of materials used in submarine pressure hull construction. This report describes the development of an explosive shock test procedure and its application to study the behaviour of HY80 plate, several shielded metal arc weldments of HY80, and several metal inert gas narrow gap HY80 weldments.

E9018M shielded metal arc weldments and 70S1 and 100S1 narrow gap weldments survived numerous shock loadings without crack development, with a total thickness reduction in excess of 16% near the center of the panels. Minor cracking developed in E11018M weldments, and complete plate brittle fracture occurred in the E7018 weldment at lower levels of plate plastic deformation. Metallurgical investigations revealed the presence of abnormal microstructural components in these weldments which caused the premature crack development in the E11018M weldment and contributed, along with the presence of slag and porosity and weld metal strain concentration, to the complete fracture of the E7018 weldment.

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HY80 STEEL

SMA WELDMENTS

NARROW GAP WELDMENTS

EXPLOSION SHOCK RESPONSE

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