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Explosion-Bulge Test Performance of Machine Welded 1 Inch Thick HY-80 Steel

Naval Research Laboratory

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DISTRIBUTION

BUSHIPS (Code 537) - (45)

ABSTRACT

Explosion-bulge tests were conducted at 0°F to evaluate the performance of machine welded HY-80 steel intended for submarine hull construction. Three types of welding methods were used to produce the weldments: (1) inert-gas-shielded metal-arc (Code C); (2) submerged arc (Code D); (3) submerged arc (Code E).

The performance of automatic weldments involving inert-gas-shielded metal-arc processes were shown to be satisfactory for applications based on "military service" loading conditions. Automatic weldments involving submerged arc processes (Code B and Code C) were characterized by high brittleness at 0°F of either the weld or HAZ. At their present state of development, submerged arc processes are not considered suitable for HY-80 applications based on "military service" loading conditions.

PROBLEM STATUS

This is an interim report; work on this problem is continuing.

AUTHORIZATION

NRL Problem M03-01

Project Nos. NS 021 200 and WT 521

INTRODUCTION

The factors which determine the performance of quenched and tempered steel weldments have been investigated by the Naval Research Laboratory as part of a continuing series of studies conducted at the request of the Bureau of Ships, Code 537. Test procedures have involved evaluations in both crack-starter[1] and explosion-bulge[2] tests. As the result of these and other studies conducted on mild and low alloy steels, NRL has presented new engineering principles and design concepts* by which the resistance to fracture of the steels may be predicted from laboratory test data[3,4,5].

For "military case" service (the structure is expected to withstand massive deformations as the result of possible explosive attack) the optimum desirable combination of high strength and concomitant high notch toughness at sub-zero temperatures is obtainable only with the quenched and tempered (Q&T) alloy type steels. One such armor type steel (STS) has long been used for Naval structural purposes involving relatively high strength levels (100,000 psi minimum Y.S.). Fabrication difficulties with this steel prompted the development of a more weldable but still relatively high strength alloy known as HY-80 (Mil-S-16216). This steel represents a modified STS composition and features a slightly lower strength than STS (80,000 to 95,000 psi Y.S.).

Previous explosion-bulge tests have shown that the HY-80 material possessed the necessary strength and weldability characteristics required for Naval armor-type structures when manually welded with G260 electrodes. An increased use of this material, therefore, was contemplated for critical Bureau construction requirements (submarine hull, torpedo defense system, etc.). Because of the large scale of the proposed construction program, it became apparent that automatic machine welding methods would be required and procedures for automatic welding of HY-80 would have to be developed and qualified.

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* These concepts permit an economical and practical specification of materials for specific service applications. Three critical fracture transition temperatures established by crack-starter tests provide a guide as to the quality of steel required. Three types of service are thus defined according to various conditions of anticipated loadings:

A. "General Case" - All portions of the structure remain within elastic loads except for small plastic points at corners, cutouts, etc. Materials whose nil-ductility transition (NDT) temperatures are below the lowest service temperature are specified.

B. "Accident Case" - Similar to A, except that a local region of a structure is deformed by collision, impact, etc. Materials whose fracture transition for elastic loading (FTE) temperatures are below the lowest service temperature are specified.

C. "Military Case" - The ultimate in loading such that the structure is deformed over a large area. Materials whose fracture transition for plastic loading (FTP) temperatures are below the lowest service temperature are specified.

Accordingly, BuShips (Code 537) established a comprehensive development and test program involving NRL, Naval Shipyards (New York and Philadelphia), an industrial shipyard (Code F), private research institutions (Code G), and three major industrial welding equipment companies (Codes C, D and E). The program requirements were outlined as follows:

Materials and techniques for machine welding of HY-80 were to be developed so as to equal the excellent performance obtainable with manual, metallic arc welding using G260 electrodes. To achieve this, it was indicated that a desirable starting point would be the development of high strength automatic weld deposits which would exceed, if possible, 20 ft-lb Charpy V at -100°F. The urgency for machine welding techniques, however, was such that all weld deposits of appropriate strength which developed 20 or more ft-lb at 0°F would be considered by the Bureau for further evaluation and possible approval for shipyard use. Further approval was construed to imply satisfactory performance of weldments in NRL explosion-bulge test. The welding procedures and conditions required for each automatic welding process were to be determined by the respective companies involved.

MATERIALS AND PRIME PLATE TESTS

The HY-80 materials used in this investigation were obtained from various sources. Table 1 lists pertinent details as to manufacturer, composition, etc. Figure 1 illustrates representative Charpy V impact transition curves for these materials. The data for two of the heats (heat No. 0187667A, Code Y and heat No. 21352, Code Z) have been reproduced from reports furnished to BuShips by C-Company[5]. The nil-ductility transition (NDT) temperatures were established in drop-weight tests to be as follows:

Heat No.	NDT (°F)	Tested by
20739 (Code Z)	-120	NRL
0187667A (Code Y)	-130 to -140	C-Company
20120 (Code Z)	-90	NRL

In relation to previous tests of other HY-80 plates, it is pertinent to note that the heat No. 20120 (Code Z) was the first HY-80 plate in which the NDT(-90°F) was established to be higher than -120°F. Additional remarks concerning this heat are deferred until a later section in this report.

EXPLOSION-BULGE TESTS OF INERT-GAS-SHIELDED METAL-ARC WELDMENTS

The C-Company was furnished plates from three different heats of HY-80 material (heat No. 0187667A (Code Y), heat No. 20120-12 (Code Z), and heat No. 21352 (Code Z)). These were automatically welded by C-Company into a total of 14 test samples (20 x 20 in. x plate thickness) in accordance with the procedures detailed in Table 2. The majority of the test samples were welded with high energy input conditions (73,500 to 84,000 Joules/in.) in order to minimize the limited weld metal porosity (equivalent to Group 1 of X-ray standards, NAVSHIPS No. 250-692-2) encountered in this welding process when low energy welds were made (37,000 to 54,000 Joules/in.). Additional details concerning weld metal studies and development program have been furnished to BuShips(6).

Explosion-bulge test results for 10 of these weldments are summarized in Table 3. It should be noted that, without exception, all of these weldments resisted 2 shots with no visible indications of failure; four of the samples resisted 3 shots with no visible failure indications; and in all cases, the ruptures which developed upon ultimate failure of the test samples were of limited size. Thus, the bulge test performance at 0°F exhibited by these weldments is considered to be good.

Figures 2 to 4 illustrate the appearance of the various HY-80 samples after the bulge tests were concluded. The numbers shown on each weldment represent sample number and test temperature (at the top) and total number of shots (lower right corner). For the high energy input welds made with heat No. 21352 (Code Z) and heat No. 0187667A (Code Y) (Fig. 2) moderate HAZ tears developed in 3 samples (Nos. 1, 2, and 5) after the 3rd shot. Only in sample No. 4, in which failure was deliberately forced by the addition of a 4th and 5th shot, were plate tears developed. As would be predicted from Charpy V results of these materials (Fig. 1), however, the plate tears are high energy absorption, shear ruptures, with no evidences of brittleness. Comparison of the low energy welding input welds (Fig. 3) with the high energy welding input welds (Fig. 4) made with HY-80 heat No. 20120-12 (Code Z) suggests that the high energy welding conditions are less favorable to the development of high quality HAZ properties. The effect of the limited weld metal porosity developed in low energy input welds appears to be insignificant. This is shown by the fact that HAZ ruptures developed after 3rd and 5th shots (Fig. 3, sample Nos. 9 and 7 respectively), and one transverse weld metal tear originating from porosity indications developed only after a 4th shot in sample No. 8.

The extensive plate tears developed in the samples shown in Fig. 4 (heat No. 20120-12, Code Z) indicate that this particular steel was not equal to expected quality of HY-80. Comparisons of Charpy data and drop-weight test results confirmed these conclusions. From inquiries of the steel mill, it was ascertained that this heat (20120) was one of the original heats of HY-80 processed by Z-Company. Heat treating (Q&T) was accomplished by dip-quenching the individual plates. Water-spray-quenching facilities have since been installed and such inferior quality material should not be expected in the future according to the manufacturer.

Conventional bulge test procedures (repeated explosive shots) permit a clear delineation of the critical regions (weld metal deposit, fusion-line zone, heat-affected zone, and prime plate areas) in which failures may start, and subsequently propagate. By superposing a crack-starter weld at the center of the bulge test sample, the test is made selective to the plate, i.e., the severity of the test conditions for HAZ and weld are decreased and those of the plate are increased. Four of these HY-80 weldments (one from each group) were explosion tested with a crack-starter weld. Figure 5 illustrates the appearance of these samples after the tests were concluded. As may be seen, the properly heat treated (spray-quenched) weldments (top sample Nos. 3 and 6) demonstrated a high resistance to plate rupture which is expected of HY-80 at service temperatures. In the dip-quenched material, however, extensive plate ruptures (partially brittle) were developed (bottom sample Nos. 10 and 14). The different extent of cracking on the composite halves of these weldments indicates that a variability in properties exists from section to section within these dip-quenched plates. As a further corroboration of such a variability, the corner (non-deformed) regions of sample No. 10 were removed and drop-weight tested. Whereas previous results for another plate of this same heat (heat No. 20120-7, Code Z) had displayed an NDT of -90°F, the corner sections from weldment No. 10 (heat No. 20120-12, Code Z) were broken in drop-weight tests to temperatures as high as -60°F. Because this heat (No. 20120, Code Z) is not representative of current HY-80 quality, additional testing of this heat was not considered practical. The results of testing of this heat, insofar as plate failures are concerned, should not be assigned to the welding method.

EXPLOSION BULGE TESTS OF SUBMERGED ARC (CODE D) HY-80 WELDMENTS

The D-Company agreed to furnish the necessary weld wire and flux required for automatically welding HY-80 steel. These were used under Shipyard conditions (New York Naval Shipyard, Code 354) for the preparation of eleven (11) explosion-bulge samples. The welding procedures employed are summarized in Table 4.

One each of the three groups of weldments furnished to NRL was explosion tested with a crack-starter weld superposed at the center of the submerged arc weld; explosion-bulge test results for the balance are summarized in Table 5. Figures 6 to 8 illustrate the appearance of these submerged arc weldments upon conclusion of the tests. All of these weldments were made with good quality HY-80 plate (heat No. 0187667A, Code Y). Generally, the bulge tests of these submerged arc (Code D) weldments are characterized by either high brittleness of the HAZ (which precluded a real test of the weld) or high brittleness of the weld (which precluded a real test of the HAZ). The HAZ degradation developed in this HY-80 heat (No. 0187667A, Code Y) is believed to result from both the relatively high interpass temperature control used for all weldments (250° to 300°F) and the relatively high energy input conditions (approximately 70,500 Joules/in.) used for the samples (Nos. 15 to 18 inclusive) shown in Fig. 6. Both weld deposits (Code D-1 wire with either flux No. 1 or No. 2) are demonstrated by these tests at 0°F to be highly inferior to that desired for welding of HY-80 prime plate. It is not possible, therefore, from these limited tests to determine which of these two weld deposits is better than the other.

EXPLOSION-BULGE TESTS OF SUBMERGED ARC (CODE E) HY-80 WELDMENTS

The E-Company was furnished HY-80 plate (heat No. 20739-6B, Code Z) from which they prepared three submerged arc weldments according to the procedures summarized in Table 6. Explosion-bulge tests of these weldments resulted in severe failures at the first shot for all samples (Fig. 9). The remarks made previously concerning HAZ degradation relative to the D-Company weldments are believed to be equally applicable to these E-Company welds. These latter welds display a tendency to develop transverse weld metal cracks after relatively small deformations. In addition, a HAZ of highly brittle character is indicated.

The severe plate tears (partially brittle) developed in weldment No. 28 indicate thatthe steel does not represent average quality HY-80. Charpy V notch specimens were machined from material removed from the lower right corner (non-deformed) region of sample No. 28. These data are shown in Fig. 10 in comparison to Charpy V curves established for other plates of this same heat (No. 20739, Code Z). The obvious variability between plates prompted inquiries of the steel mill concerning processing procedures used for this heat. It was determined that this heat represented an unusually small melt from which non-standard plate sections were produced. Consequently, since this heat (No. 20739, Code Z) is not representative of current specification quality HY-80, further studies with this material were discontinued.

SUMMARY AND CONCLUSIONS

Generally, the results of this investigation have corroborated the previously established fact that specification quality HY-80 material is highly notch tough, and demonstrates FTP characteristics (complete resistance to brittle fracture) at temperatures of -20°F and higher. It is also shown that processing variables employed for the plate (heat treatment, cross-rolling, etc.) may result in significant variations in notch toughness. The development of a notch ductility specification for HY-80 should eliminate this difficulty in the future. Effects of welding conditions on HAZ properties are to be expected because of the ready response of this Q&T steel to thermal changes. The welding conditions desirable for HY-80 weldments are indicated to be those conducive to the development of fast cooling rates in the HAZ. Other studies[6] have indicated that the best metallurgical structure in the HAZ of HY-80 would be developed when the energy input of welding is limited to a maximum of approximately 30,000 Joules/in. (e.g. 320 amps, 27 volts and 18 ipm minimum travel). Bulge tests of the automatically welded samples reported herein have demonstrated HAZ deficiencies are developed in high energy input welds of HY-80. In comparison, the effect of moderate scattered porosity developed in the low energy welds of the C-Company weldments was shown to be much less significant to the bulge test performance of HY-80 weldments, than was the use of high energy input welding conditions.

With respect to the various automatic welding procedures investigated herein, the following general conclusions are warranted for performance at 0°F:

1. Weldments involving inert-gas-shielded metal-arc (C-Company) and specification quality HY-80 material, have demonstrated the best general performances at 0°F of any armor-type steel previously investigated(7,8). This is due to the presence of a notch ductile weld metal and the minimizing of HAZ degradation which always occurs to some extent in a weldment. Further improvements may possibly be developed by the use of low energy input welding.

2. For the two weld deposits and the welding conditions described, (and specification quality HY-80) the D-Company submerged arc process weldments were characterized by high brittleness of either, or both, the weld and HAZ. Accordingly, in the present state of development this process cannot be considered suitable for automatic welding of HY-80 structures required to meet FTP performance characteristics at 0°F.

3. From the limited tests involving poor quality HY-80 material, definite conclusions concerning E-Company weldments cannot be made with assurance. However, for the one weld deposit, and the welding conditions tested, the ready propensity for transverse weld metal cracking and severe HAZ damage are evident. Thus, in its present state of development, the E-Company submerged arc process likewise cannot be considered suitable for automatic welding of HY-80 structures.

REFERENCES

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2. Hartbower, C. E. and Pellini, W. S., "Explosion-Bulge Test Studies of the Deformation of Weldments," WELDING JOURNAL, June 1951.

3. Puzak, P. P. and Pellini, W. S., "Effect of Temperature on the Ductility of High-Strength Structural Steels Loaded in the Presence of Sharp Cracks," NRL Report 4545, June 1955.

4. Puzak, P. P. and Pellini, W. S., "Evaluation of the Significance of Charpy Tests for Quenched and Tempered Steels," WELDING JOURNAL Research Suppl., June 1956.

5. Pellini, W. S. and Puzak, P. P., "Development of An Engineering Approach to the Problems of the Brittle Fracture of Steels," to be issued as NRL Report.

6. Felmley, C. R. and Bielenberg, J. G., "Summary Report on the Welding of HY-80 Steel by Inert-Gas-Shielded Metal-Arc Welding," Bureau of Ships Contract No. NObs 72087, Index No. NS-021-200, 27 January to 27 June 1956.

7. Pellini, W. S. and Eschbacher, E. W., "Investigation of the Performance of 1-In. S.T.S. Weldments of G260 and 25-20 Types," NRL MEMO Report 191, July 1953.

8. Puzak, P. P. and Pellini, W. S., "Explosion-Bulge Test Performance of 1-In. S.T.S. Semi-Automatic Inert-Gas Metal-Arc Weldments," NRL MEMO Report 391, November 1954.

TABLE 1

Manufacturer	Heat No.	Thickness In.	%C	%Mn	%Cr	%Ni	%Mo	Source
Code Y	0187667A	1	.18	.26	.99	2.26	.21	New York NSY
Code Z	20739	1	.14	.22	.95	2.23	.26	Phila. NSY
Code Z	21352	15/16	.14	.29	.99	2.17	.10	Code F
Code Z	20120	1	.18	.33	.99	2.11	.29	Phila. NSY

TABLE 2

MATERIALS AND PROCEDURES FOR INERT-GAS-SHIELDED METAL-ARC EXPLOSION TEST SAMPLES

Sample No.	C-Company No. 1009-	Prime Plate Heat No.	Thickness (in.)	Welding Conditions				
				Amps.	Volts	Speed ipm	Energy Joules/in.	No. of Passes
1	-16	Code Z 21352	15/16	310/340	27	6 to 7.5	73,500 to 84,000	6
2	-19	Code Z 21352	15/16	310/340	27	6 to 7.5	73,500 to 84,000	6
3	-18	Code Z 21352	15/16	310/340	27	6 to 7.5	73,500 to 84,000	6
4	-27	Code Y 0187667A	1	310/340	27	6 to 7.5	73,500 to 84,000	6
5	-25	Code Y 0187667A	1	310/340	27	6 to 7.5	73,500 to 84,000	6
6	-24	Code Y 0187667A	1	310/340	27	6 to 7.5	73,500 to 84,000	6
7	-8	Code Z 20120-12	1	330/360	25	10 to 13.5	37,000 to 54,000	6
8	-11	Code Z 20120-12	1	330/360	25	10 to 13.5	37,000 to 54,000	6
9	-10	Code Z 20120-12	1	330/360	25	10 to 13.5	37,000 to 54,000	6
10	-9	Code Z 20120-12	1	330/360	25	10 to 13.5	37,000 to 54,000	6
11	-22	Code Z 20120-12	1	310/340	27	6 to 7.5	73,500 to 84,000	6
12	-29	Code Z 20120-12	1	310/340	27	6 to 7.5	73,500 to 84,000	6
13	-28	Code Z 20120-12	1	310/340	27	6 to 7.5	73,500 to 84,000	6
14	-21	Code Z 20120-12	1	310/340	27	6 to 7.5	73,500 to 84,000	6

Joint preparation for all weldments was 45° VV butt, 3/32-in. land and 3/32-in. root opening. All welds were made with C-1 wire from C-Company heat No. 13145. Shielding gas of Argon plus one percent Oxygen was used at a flow rate of 60 cfh.

TABLE 3

EXPLOSION-BULGE TEST DATA FOR 45° VV BUTT INERT-GAS-SHIELDED METAL-ARC WELDMENTS

Sample No.	Prime Plate Heat No.	Test Temp. (°F)	1st Shot	2nd Shot	3rd Shot	4th Shot	5th Shot
1	Code Z 21352	0	N	N	F		
2	" " "	0	N	N	F		
4	Code Y 0187667A	0	N	N	N	N	F
5	" " "	0	N	N	F		
7	Code Z 20120-12	0	N	N	N	N	F
8	" " "	0	N	N	N	F	
9	" " "	0	N	N	F		
11	" " "	0	N	N	F		
12	" " "	0	N	N	F		
13	" " "	0	N	N	N	N	F

N = No visible indications of failure.

F = Failure as shown in photographs (Fig. Nos. 2 to 5).

TABLE 4

MATERIALS AND PROCEDURES FOR SUBMERGED ARC CODE D
EXPLOSION TEST SAMPLES

Sample No.	New York NSY No.	Interpass Temp.($^{\circ}$F)	D-1 Wire + Flux No.	Amps.	Volts	Speed ipm	No. of Passes
15	L-2	300	D-2	550	32	15	8
16	L-3	300	D-2	550	32	15	8
17	L-4	300	D-2	550	32	15	8
18	L-5	300	D-2	550	32	15	8
19	L-6	300	D-2	400	26	20 to 30	21
20	L-7	300	D-2	400	26	20 to 30	21
21	L-8	300	D-2	400	26	20 to 30	21
22	L-9	300	D-2	400	26	20 to 30	21
23	L-10	250	D-3	400	26	20 to 30	24
24	L-11	250	D-3	400	26	20 to 30	24
25	L-12	250	D-3	400	26	20 to 30	24

All weldments were made with Code Y Heat No. 0187667A, HY-80 plate, using 60° VV butt (1/4-in. deep, manual G260 back-up, 5 passes), and 3/16-in. root opening.

TABLE 5

EXPLOSION-BULGE TEST DATA FOR 60° VV BUTT
SUBMERGED ARC CODE D WELDMENTS

Sample No.	Test Temp. (°F)	1st Shot	2nd Shot	3rd Shot
15	0	N	N	F
16	0	N	N	F
17	0	F		
20	0	N	HAZ	F
21	0	N	HAZ	F
22	0	N	F	
23	0	N	F	
24	0	F		

N = No visible indications of failure

HAZ = Evidence of slight separation of HAZ

F = Failure as shown in photographs (Fig. Nos. 6 to 8)

TABLE 6

MATERIALS AND PROCEDURES FOR SUBMERGED ARC CODE E EXPLOSION TEST SAMPLES

Sample No.	E-Company No.	Interpass Temp.(°F)	E-1 Wire + Flux No.	Amps.	Volts	Speed ipm	No. of Passes	Root Pass
26	24669	225	E-2	600	30	24	16	G230
27	24673	225	E-2	600	30	24	16	G260
28	24676	225	E-2	600	30	10	7	G230

All weldments were made with Code Z Heat No. 20739-6B, HY-80, plate using 60° single V, no nose, and 1/8-in. root opening joint preparation. Root and back seal pass made with low hydrogen electrodes as shown above.

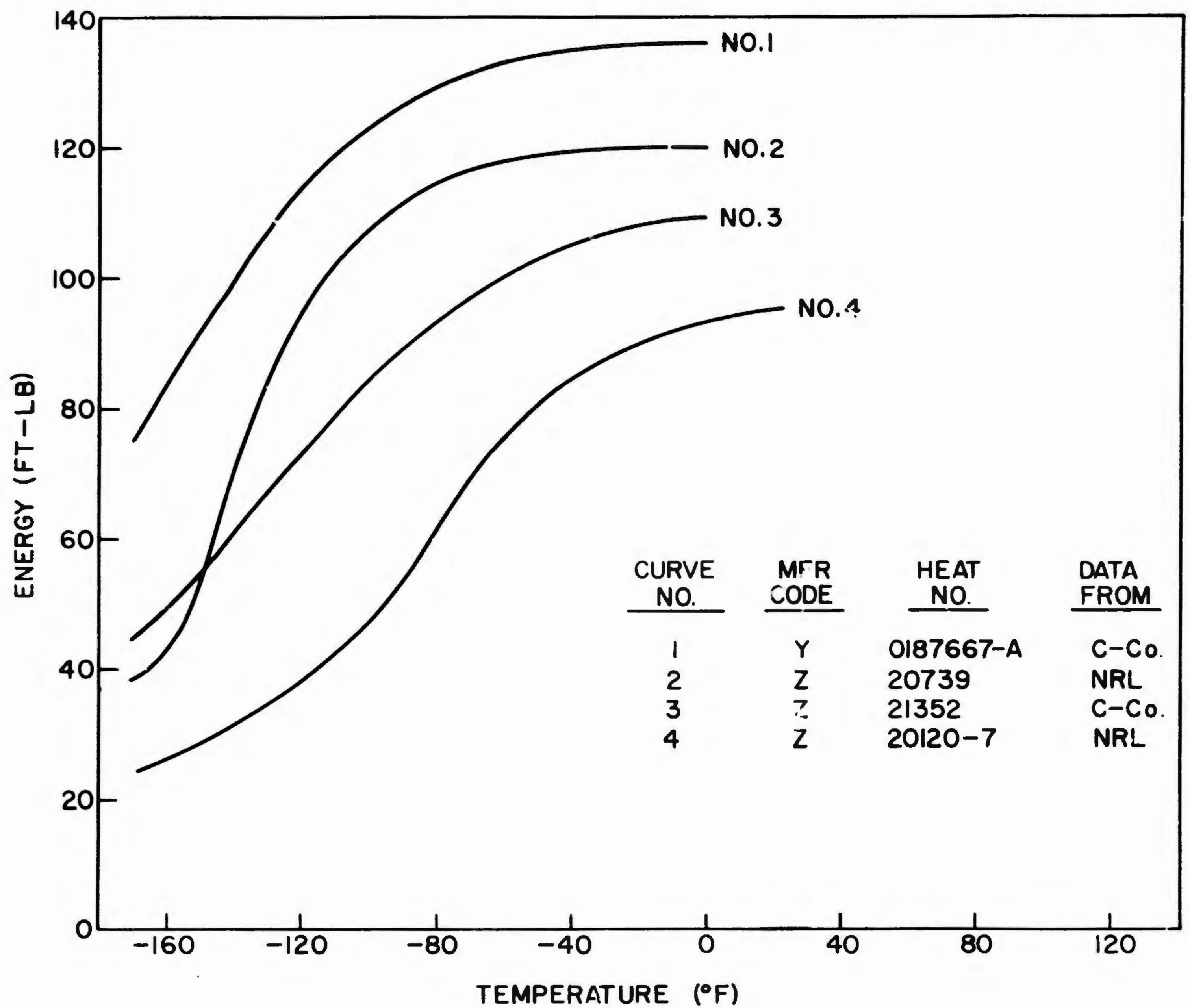

Figure 1 - Charpy V transition curves for HY-80 prime plate

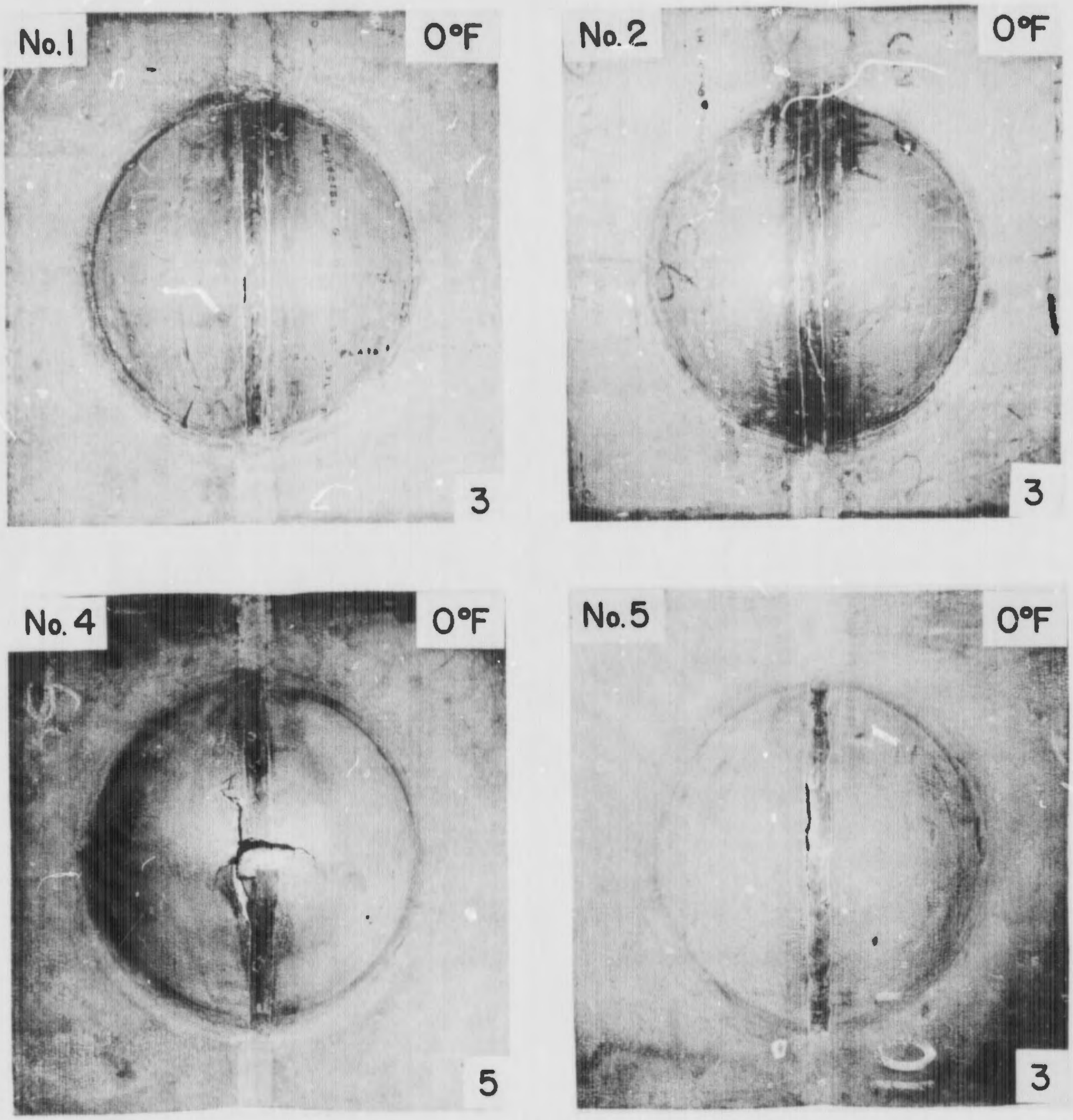

Figure 2 - Explosion bulge test fracture characteristics of high welding energy input inert-gas-shielded metal-arc weldments. (Top samples Code Z, HY-80 heat No. 21352, bottom samples Code Y, HY-80 heat No. 0187667A.)

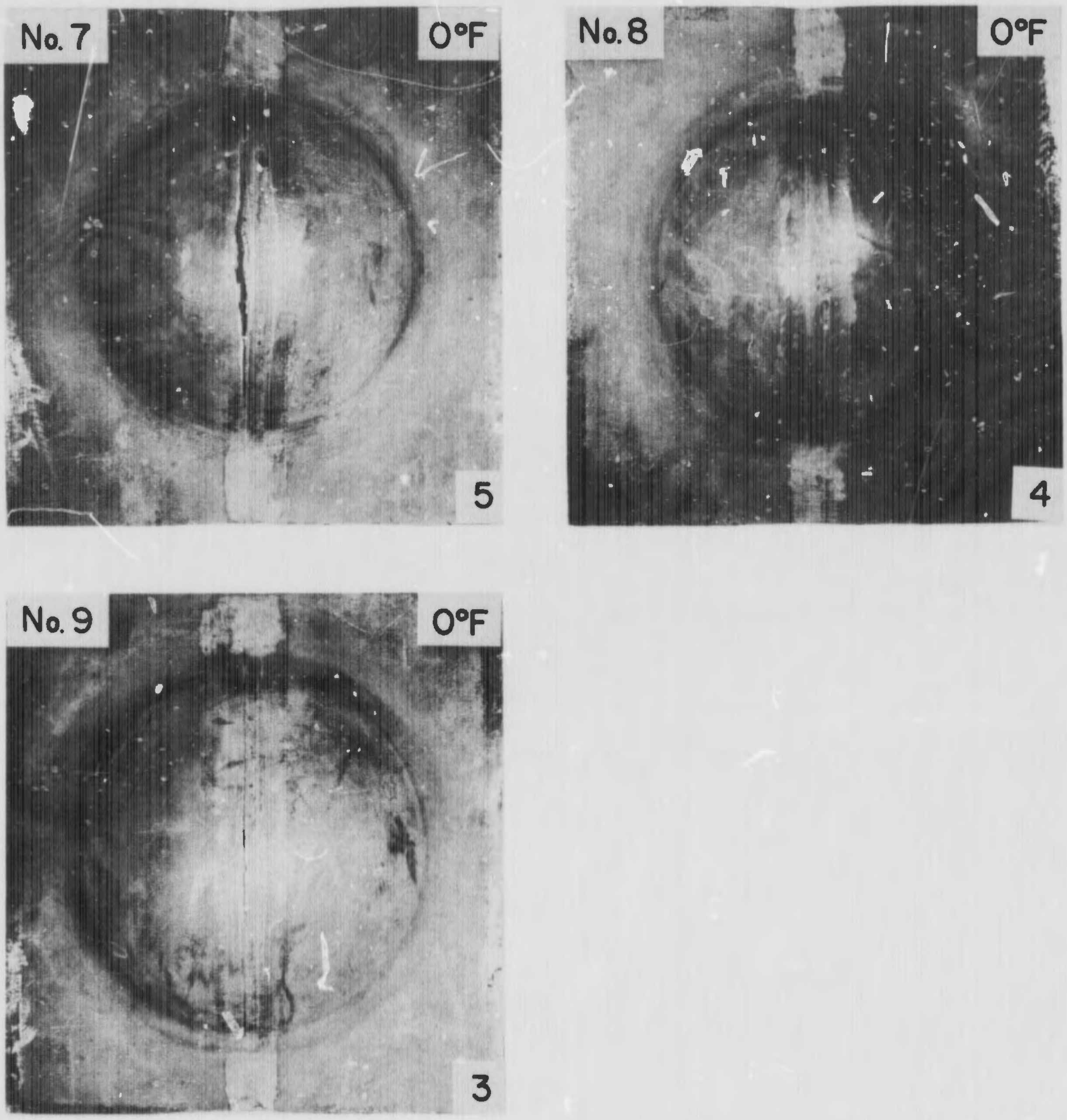

Figure 3 - Explosion bulge test fracture characteristics of low welding energy input inert-gas-shielded metal-arc weldments. (Code Z, HY-80 heat No. 20120-12.)

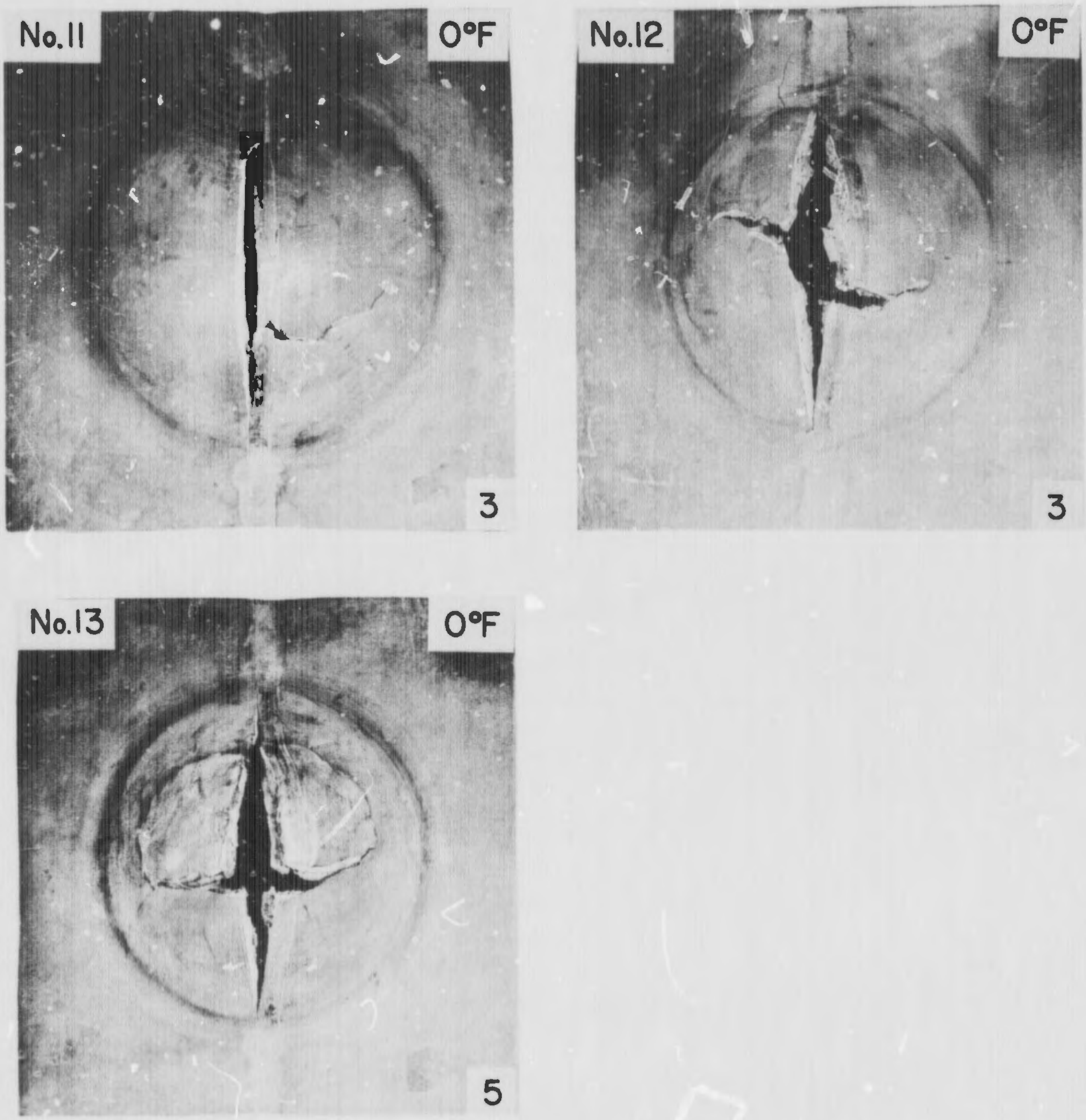

Figure 4 - Explosion bulge test fracture characteristics of high welding energy input inert-gas-shielded metal-arc weldments. (Code Z, HY-80 heat No. 20120-12.)

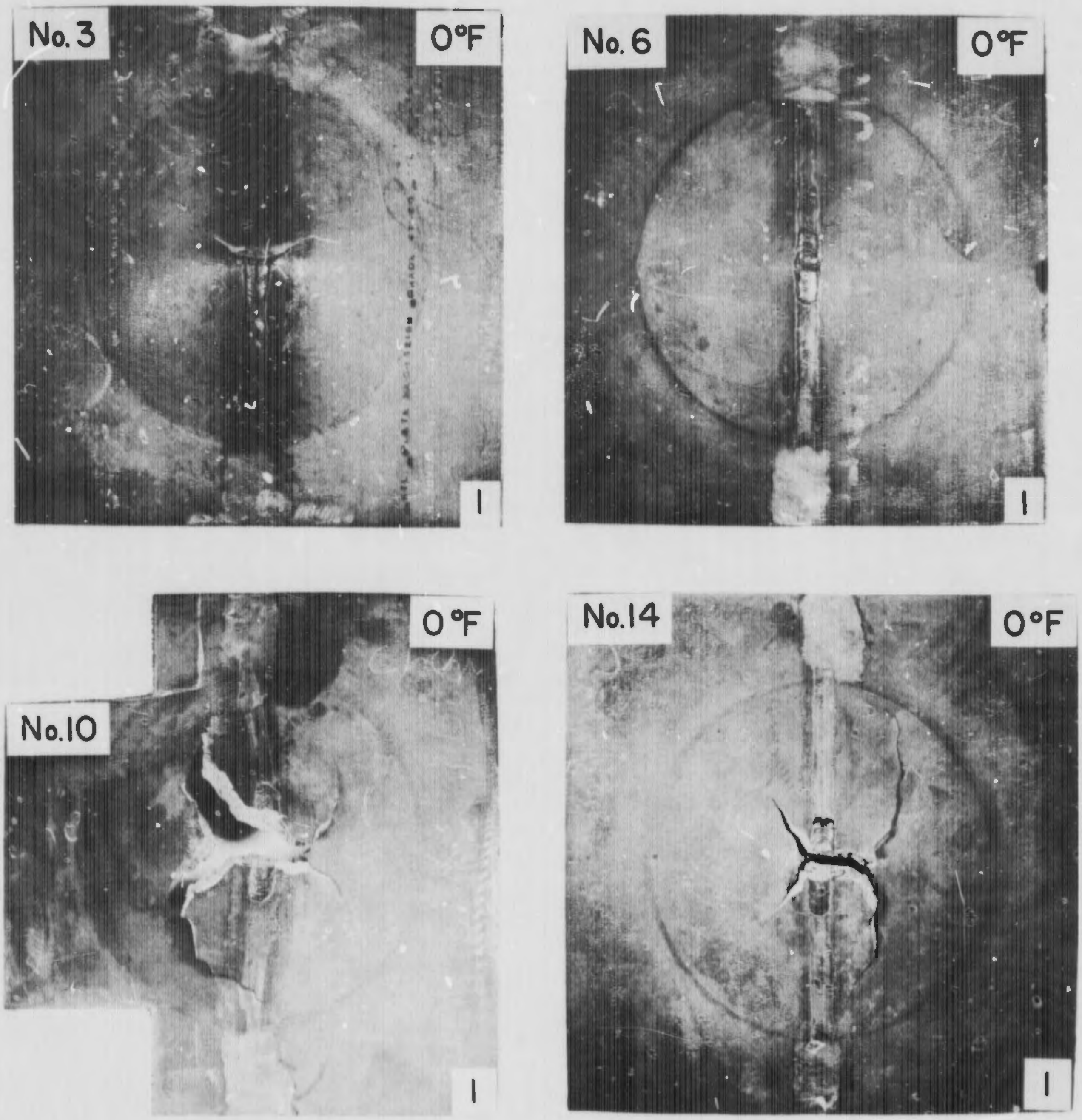

Figure 5 - Fracture characteristics of inert-gas-shielded metal-arc weldments modified to incorporate crack-started weld. (Top samples are sprayed-quenched HY-80; bottom samples are dip-quenched.)

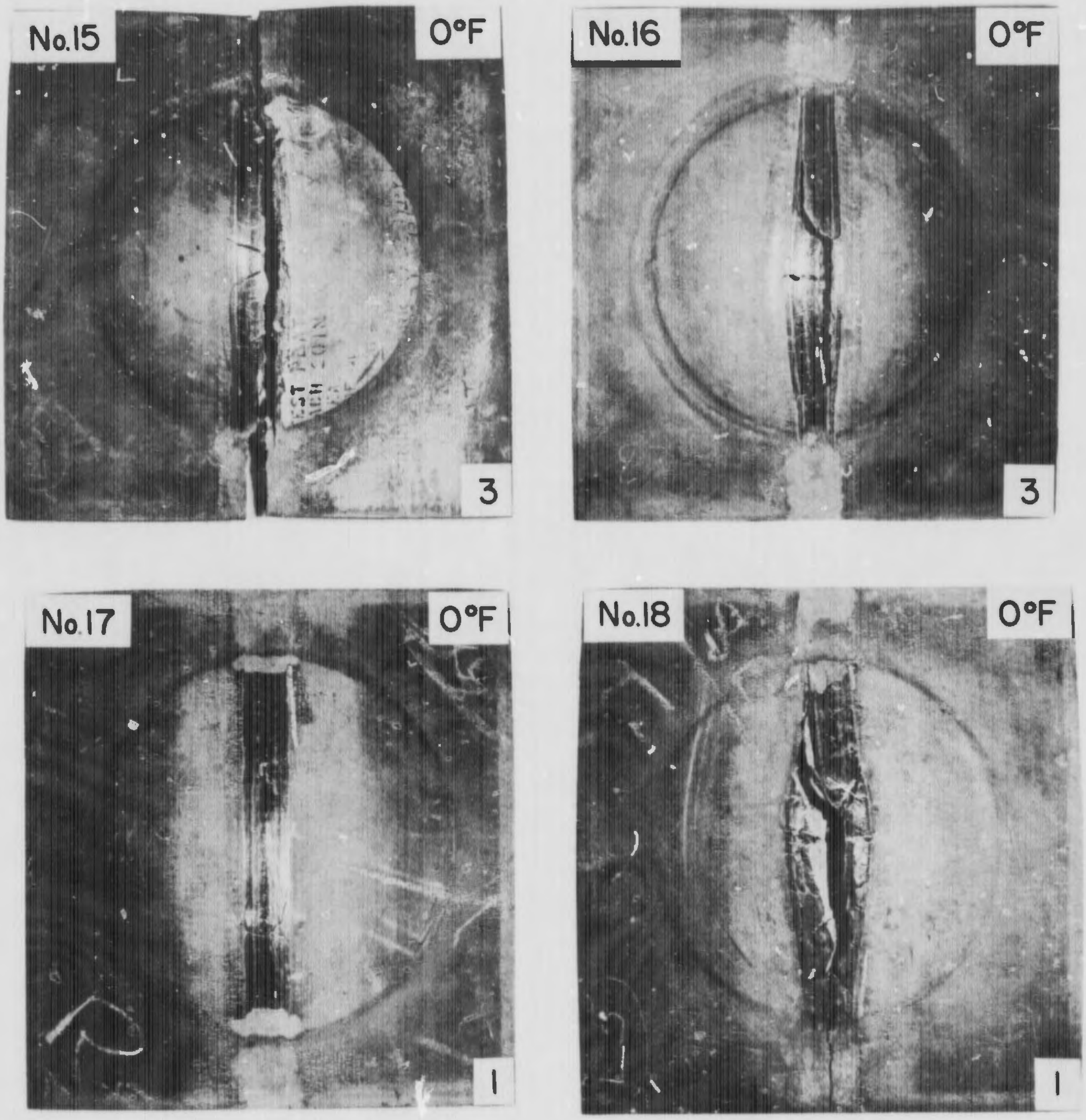

Figure 6 - Fracture characteristics of high welding energy input submerged arc (Code D1 wire + D2 flux) weldments. (Sample No. 18, bottom right, was tested with crack-starter weld.)

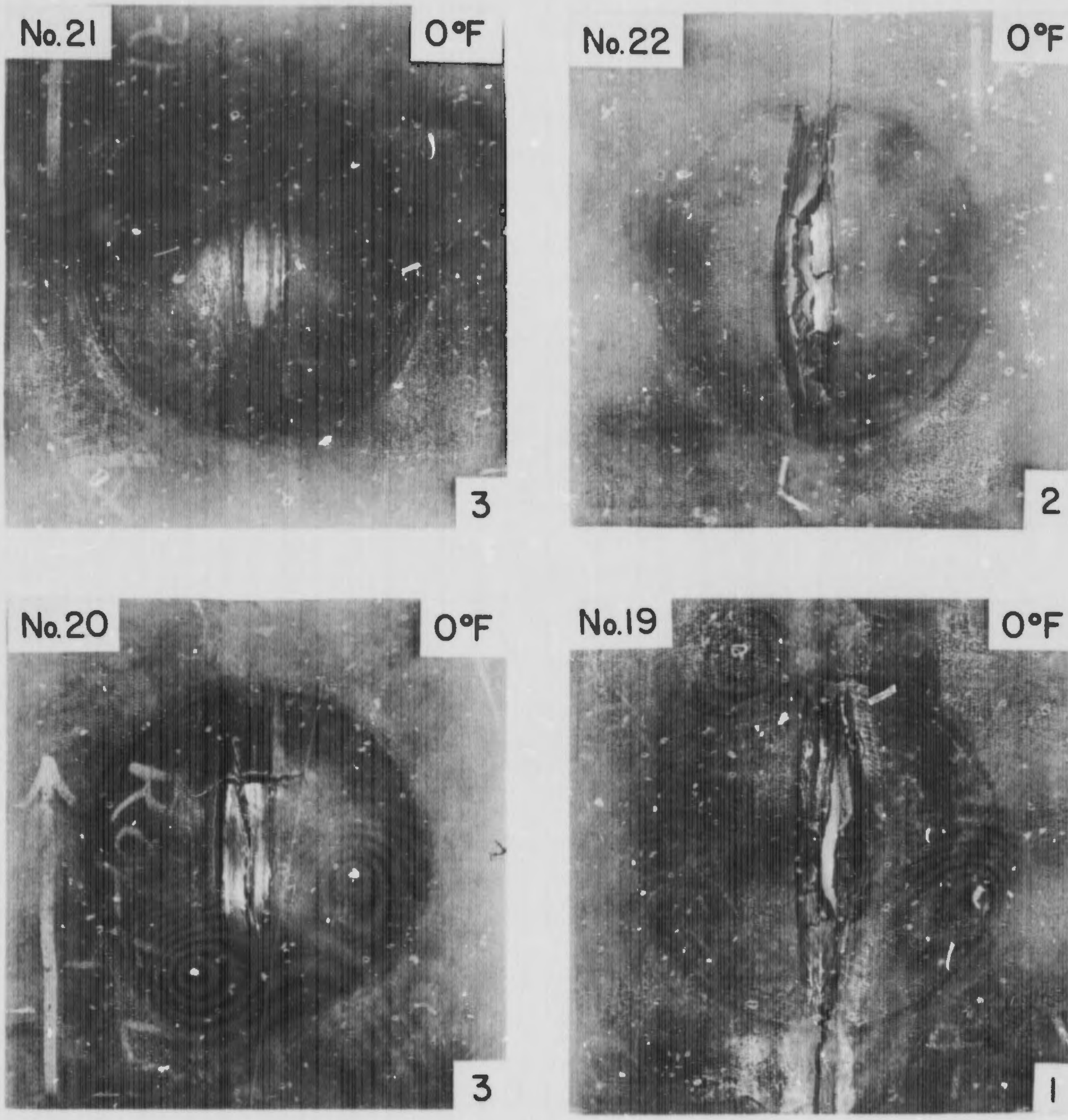

Figure 7 - Fracture characteristics of low welding energy input submerged arc (Code D1 wire + D2 flux) weldments. (Sample No. 19, bottom right, was tested with crack-starter weld.)

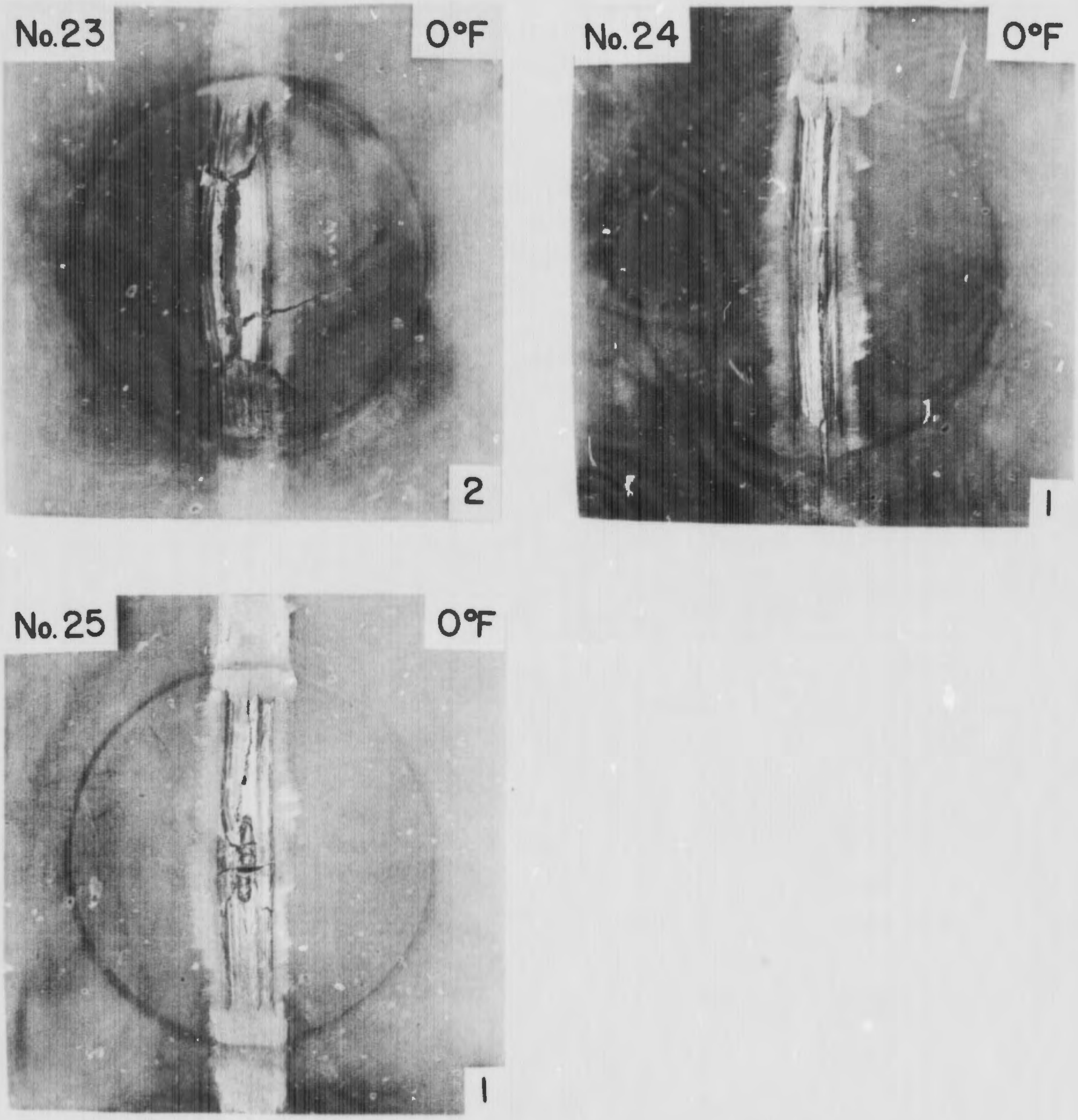

Figure 8 - Fracture characteristics of low welding energy input submerged arc (Code D1 wire + D2 flux) weldments. (Sample No. 25, bottom left, was tested with crack-starter weld.)

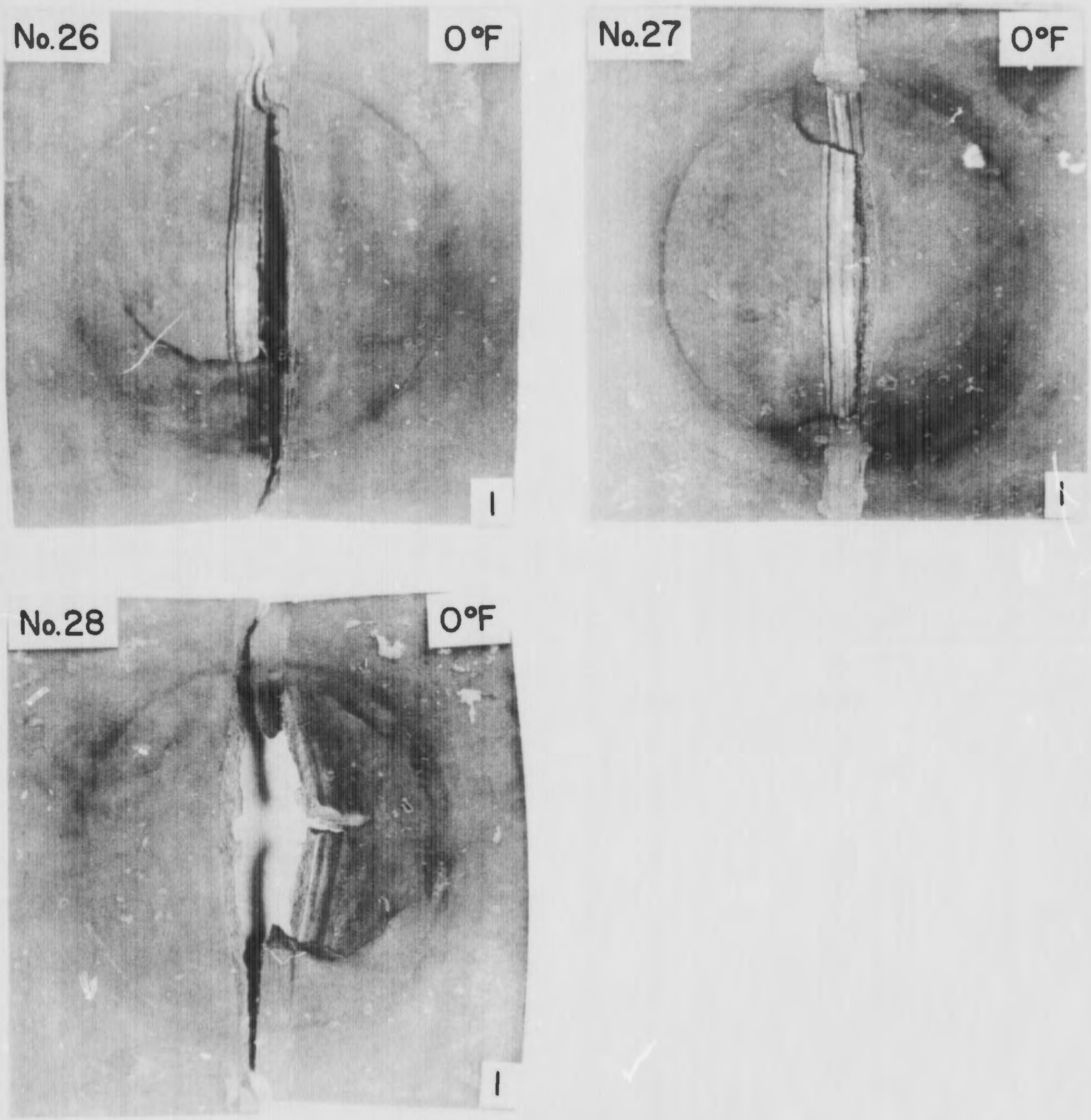

Figure 9 - Explosion bulge test fracture characteristics of submerged arc (Code E) weldments. (HY-80 is Code Z heat No. 20739)

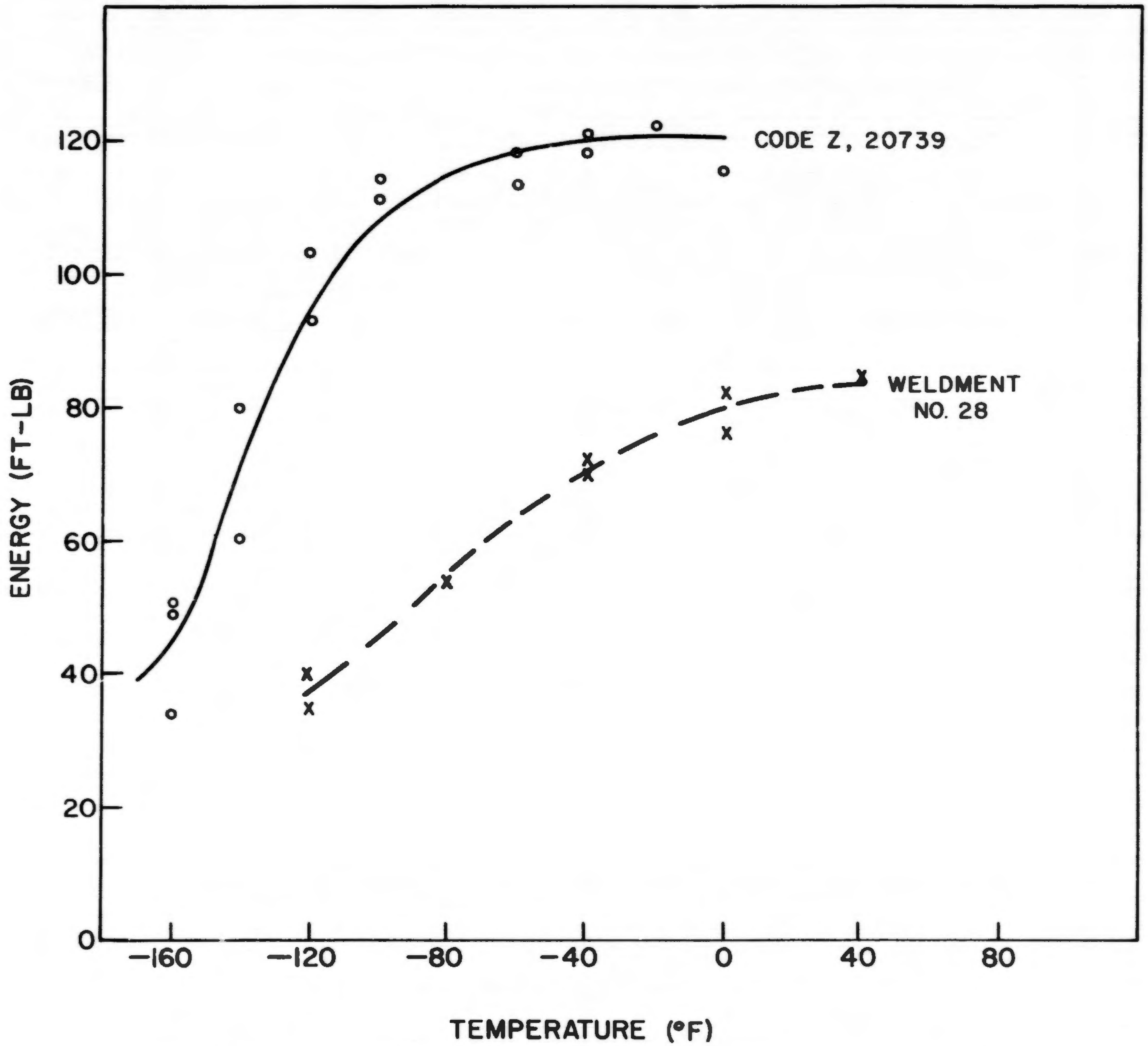

Figure 10 - Charpy V test results indicating variability between different plates of HY-80 heat No. 20739 (Code Z)