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Mechanical Considerations in Fracture Characterization of Narrow Gap Weldments

The Dynamic Tear (DT) test provides a reliable measurement of fracture toughness, whereas the Charpy V-notch test is inadequate and leads to incorrect conclusions regarding fracture mode propagation features of the metal

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ABSTRACT. The Dynamic Tear (DT) test provides a reliable measurement of fracture toughness under limit severity mechanical conditions. In this investigation, the DT test was used to characterize the fracture toughness for a weldment of 2 in. thick A-543 plate prepared by the automatic narrow gap (N-G) welding process. The DT test specimen was modified through the use of side grooves.

Fracture toughness of the weld metal was found to be dependent upon welding position: the flat (1200) and near vertical (0200) weld positions produce high upper shelf energy values equivalent to that of the base metal, while the 0400 (near vertical) and 0600 (overhead) positions indicate a shelf level toughness approximately one-half that of the plate. Results of ⅝ in. DT tests were consistent with values from full-thickness, 2 in. DT specimens. The Charpy V-notch or C_v test produced a misleading indication of the transition temperature range and the temperature at which the upper shelf, full ductility develops.

The uniquely limited width of the N-G weld enhanced the fracture toughness of the weldment in the transition temperature range and on the upper shelf when the crack tip plastic zone size exceeded the weld zone and entered the A-543 plate. This increased the resistance to fracture propagation through involvement of the tough plate metal.

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Introduction

Fracture toughness may be described as the resistance of a metal to the initial extension and subsequent propagation of a crack. Weld regions represent "composite" materials for which the mechanical conditions for initiation and propagation may be different—at least in degree. Narrow gap weldments feature interesting differences in these respects which are examined in this paper by means of the new Dynamic Tear (DT) test.[1-3] The DT test provides a sensitive and quantitative determination of the energy required to propagate a dynamic fracture for mechanical conditions of limit severity. These include maximum crack sharpness for initiation of fracture and dynamic loading. The measured energy is directly relatable to the plastic zone size developed under these adverse conditions.

To produce the mechanical restraint at the crack tip of the specimen similar to that which will exist at the tip of a through-thickness flaw in a structure, the thickness of the specimen must be the same as the metal used in the structure. The exceptions to this rule relate to metals of relatively low and very high fracture toughness. For these conditions, subsized specimens provide adequate measurement of resistance to fracture instability for most engineering purposes. The other specimen dimensions must be sufficient to the extent that any additional increase in the dimensions will have no effect on the crack tip constraint. The DT test can be dimensioned to represent a full-thickness test, and fracture toughness levels for which thickness effects apply in fracture propagation can be determined. For dynamic fracture propagation, the temperature transition range for which thickness effects are of engineering importance is relatively narrow.[4] Thus, subsized DT specimens may be used to establish temperature transition aspects of thick sections with confidence.

Standardized DT tests of $^5/_8$ and 1

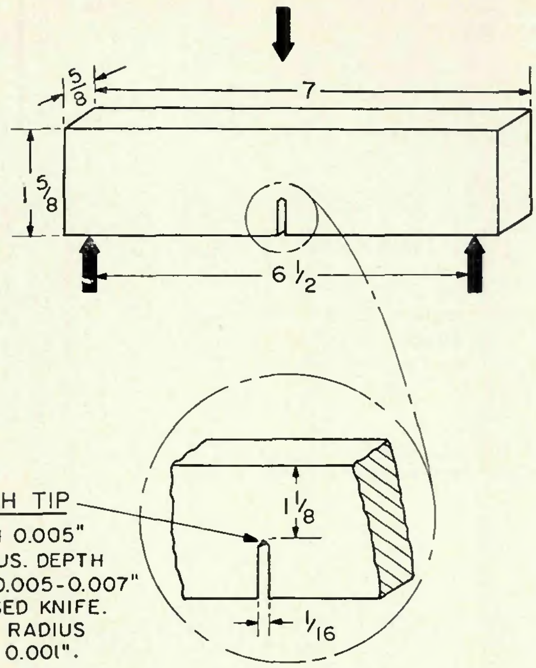

Fig. 1—Dimensions of the 5/8 in. thick DT test specimen. This subsize DT specimen substitutes a deep-machined and pressed tip notch for the embrittled crack starter weld of the conventional, full-thickness DT specimen

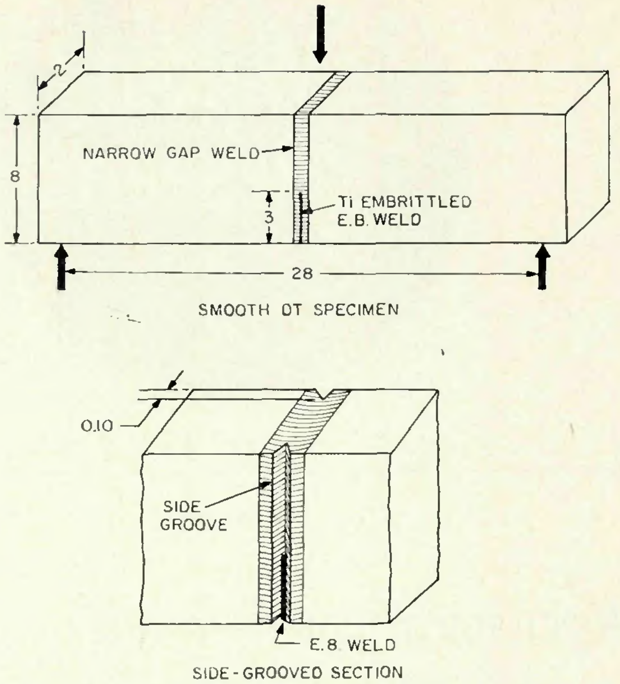

Fig. 2—Configurations of (top) the full-thickness (2 in.) DT specimen employed to measure the fracture toughness of the narrow gap welds in 2 in. thick A-543 plate and (bottom) the side-grooved DT specimen

in. thick specimens have been developed for general engineering use. Correlations of data obtained for these two dimensions of conventional DT tests have confirmed equivalent predictive capabilities.[4, 5] The $^5/_8$ in. thick specimen employs a considerably smaller quantity of material than the 1 in. thick specimen and substitutes a deep-machined and pressed-tip notch ($^5/_8$ in. DPN) for the embrittled crack starter weld—Fig. 1.

Narrow Gap Process Weldments

The automatic narrow-gap (N-G) welding process represents a modification of the conventional gas metal-arc process for deposition of filler metal at very low heat inputs. The N-G process employs two filler metals or electrodes—a lead wire and a trail wire in tandem—each cast toward a different side of a butt joint. In the simulated structural weldment studied in this investigation, the 0.035 in. diameter electrodes were shielded by a gas mixture containing 80% argon and 20% CO_2. The electrodes travel along the square butt joint at a speed of 45 ipm, providing a combined heat input of 18 kilojoules/in.[6] This heat input is approximately $^1/_3$ to $^1/_2$ the specified welding heat inputs allowed for A-543 structural weldments.[7] The experimental weldments were prepared by an expert source for Navy investigations which included the subject studies.

The fracture toughness test investigations involved a circumferential weld joining two short sections of a large-diameter semicylindrical plate. The A-543 plate was 2 in. thick; the percentage (%) compositions of the base metal and filler metal are presented below:

	Base Metal	Filler Metal
C	0.18	0.07
Mn	0.32	1.52
Si	0.21	0.73
Ni	2.03	1.04
Cr	1.40	0.03
Mo	0.35	0.32
Cu	0.03	0.54
P	0.012	0.004
S	0.019	0.006
V	0.005	0.01
Cb		0.001
Al		0.02

The C-shaped section consisted of two curved A-543 plates separated by a $^1/_4$ in. wide square butt joint.[5] The welding carriage rode on tracks attached to the plates, permitting the welding equipment to automatically deposit a weld between the 12 o'clock (1200) and 6 o'clock (0600) positions. The semi-cylindrical shape afforded an opportunity to make a comparison of deviations in toughness for different weld positions. The four positions investigated were: flat (1200), almost vertical (0200 and 0400), and overhead (0600) welding positions. Nominally, preheat and interpass temperatures of 250° F were maintained through completion of the weldment.

Temperature Dependence of the Plastic Zone

The restricted width of the N-G weld had a pronounced effect on the fracture path as the testing temperature was increased due to the dependence of the plastic zone size on temperature. The crack tip plastic zone is an area of plastically deformed metal which impedes the initial extension and propagation of the fracture. The size of the plastic zone is a function of the stress-intensity parameter K_1 and the yield strength (YS) as follows:

$$2r_y = 2C(K_I/YS)^2 \qquad (1)$$

here C is a constant which depends on the stress state.[8] Because K_I increases and YS decreases with rising temperature, the plastic zone size ($2r_y$) grows rapidly as the test temperature is raised.

For the N-G weldment, the effect of an increasing plastic zone size with temperature must be considered for both the weldment width as well as the weldment thickness. In a 2 in. thick DT specimen the first effect of increasing temperature results in a plastic zone which will grow large compared to the $^1/_4$ in. width of the N-G weld but will still remain small relative to the thickness. This situation occurs at the low end of the transition temperature range. A plane strain stress state will exist and the plastic zone size formula will be:

$$2r_y = (^1/_{3\pi})(K_I/YS)^2 \qquad (2)$$

The most notable physical manifestation of the increasing plastic zone size is the appearance of shear lips on the fracture surface. At low temperatures and small plastic zones, the fracture surface is flat and the plane strain fracture propagates through the weldment. As the temperature is raised and the plastic zone enters the base metal, the fracture may still move through the weldment; but the resistance to fracture propagation has been enhanced by the high toughness of the base metal which is now contributing to the fracture process. At the higher temperatures the shear lips resulting from the rapidly growing plastic zone penetrate into the A-543 plate. The fracture propagation energy then becomes a combination of energy to fracture the weld metal and to propagate fracture in the A-543 base metal.

The problem of confining the fracture plane to the weld metal at the higher DT testing temperatures was noted when the first full-thickness DT specimen was fractured at room temperature. The fracture propagated out of the weld metal and into the adjoining plate as shear lips formed, resulting in so great an increase in the resistance to crack extension that the fracture arrested after exceeding the testing machine capacity. This observation led to investigations of the effects of side grooving for the subsequent DT specimens. The side grooves were machined to a depth of 5% of the base metal thickness on each side of the weld and contained an included angle of 60 deg and a notch root radius of 0.002 in. The purpose of the side grooves was to eliminate the shear lips and cause the crack to follow a fracture path in the weld metal.

The side grooving technique is not a standard part of the DT test procedure. However, it was employed in this specific investigation because of the need to constrain the fracture plane to the unique, limited width of the N-G weldment. All of the full-thickness (2 in.) and subsized $^5/_8$ in. DT results discussed in this paper including the low temperature test values were obtained with side-grooved DT specimens. Although the small plastic zone formed in the low temperature tests allowed the fracture to remain in the weld metal without the use of the side grooves, these specimens were side-grooved to retain geometric similitude and permit the test results to be compared directly with the higher temperature tests.

Table 1—Tensile and Charpy V-Notch Data for A-543 Plate and Narrow Gap Process Weldment

Tensile test data:

A-543 plate WR orientation	Yield strength (0.2% offset), ksi	Tensile strength, ksi	Elongation in 2 in., %	Reduction of area, %
12 o'clock	85.4	102.4	24.5	67.4
2 o'clock	85.5	104.0	23.6	65.3
4 o'clock	84.8	102.4	23.2	66.7
6 o'clock	85.0	103.1	24.3	65.0
Transweld	All transweld oriented specimens broke out of the weld region in the 2 in. gauge length but away from the heat-affected zone with apparent strength values equivalent to that represented above for the base metal.			

Charpy V-notch data:

Temperature, °F	Test energy, ft-lb: A-543 plate WR orientation	12 o'clock weld	2 o'clock weld
120	—	80	—
80	90	78	84
30	95	74	78
0	98	78	83
− 20	—	—	74
− 30	—	69	—
− 40	—	—	78
− 60	92	67	80
− 80	89	54	73
−100	76	50	54
−120	62	—	55
−140	52	34	—
−160	40	—	40
−200	29	—	—

Fracture Toughness Test Results

Transverse tensile and Charpy V-notch (C_v) data for the 2 in. thick A-543 plate are reported in Table 1. All of the room temperature tensile specimens broke out of the weld and away from the heat-affected zone but within the 2 in. gauge length. This implies that the nominal yield strength of the N-G weld metal is moderately higher than the yield strength value of 85 ksi reported for the A-543 base metal (Table 1).

Dimensions of the 2 in. thick DT specimen are presented in Fig. 2 for both a smooth and side-grooved configuration.

The energy measurements from the $^5/_8$ in. side-grooved DT specimen are listed in Table 2 and are plotted against temperature for two weld positions and the A-543 plate in Fig. 3. Little difference in shelf level ener-

Table 2—Side-Grooved (SG) $^5/_8$ in. Dynamic Tear Test Data for A-543 Plate and Narrow Gap Process Weldment at 12 and 2 O'Clock Positions

Temperature, °F	A-543 plate WR orientation SG-DT test energy, ft-lb	12 o'clock weld SG-DT test energy, ft-lb	2 o'clock weld SG-DT test energy, ft-lb
80	545	563	547
30	555	547	537
0	590	417	480
− 30	542	250	257
− 60	411	222	214
− 80	307	—	—
−100	251	—	—
−120	208	111	132

Table 3—Dynamic Tear (DT) Test Data for A-543 Plate and Narrow Gap Process Weldment at 4 and 6 O'Clock Positions

Temperature, °F	A-543 plate WR orientation SG-DT test energy, ft-lb	4 o'clock weld SG-DT test energy, ft-lb	6 o'clock weld SG-DT test energy, ft-lb
Side-grooved (SG) 2 in. dynamic tear test data:			
30	18,500	10,200	8,695
0	18,150	8,850	9,895
− 30	17,490	9,300	5,860
− 60	11,225	7,500	6,840
− 80	6,075	—	—
−100	3,300	—	—
Side-grooved (SG) $^5/_8$ in. dynamic tear test data:			
70	582	369	278
30	563	269	324
0	589	—	200
− 30	515	181	220
− 60	445	144	114
− 80	267	—	—
−100	330	—	—
−120	181	—	—

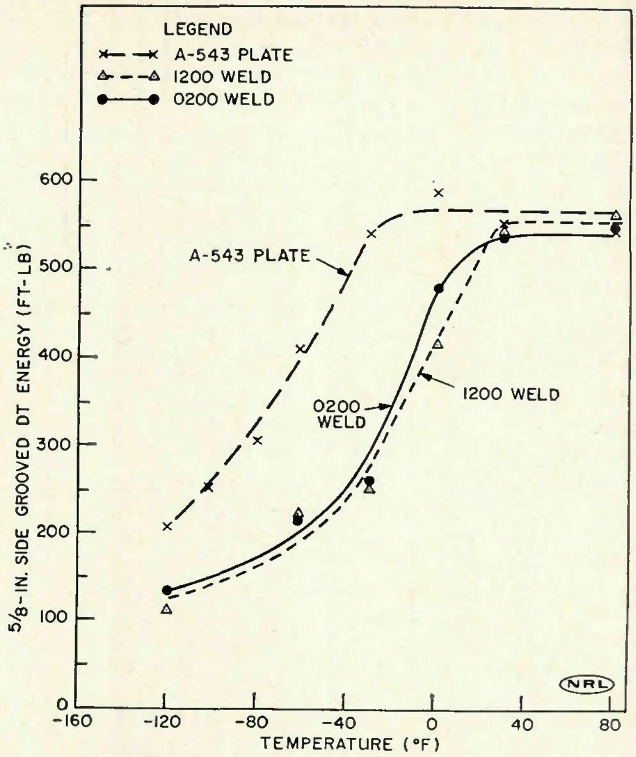

Fig. 3—Comparison of the fracture toughness of the flat (1200) and near vertical (0200) welds with A-543 plate using the subsize DT specimen. Upper shelf (full ductility) level energy values of welds are similar to that of A-543 plate

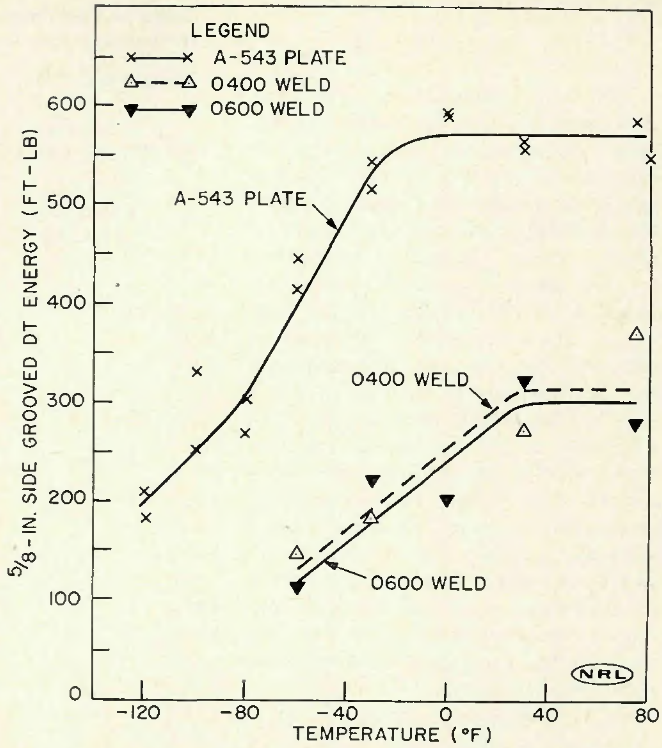

Fig. 4—Fracture toughness of near vertical (0400) and overhead (0600) welds as compared with the plate. Upper shelf energy values of welds are approximately half that of the base metal

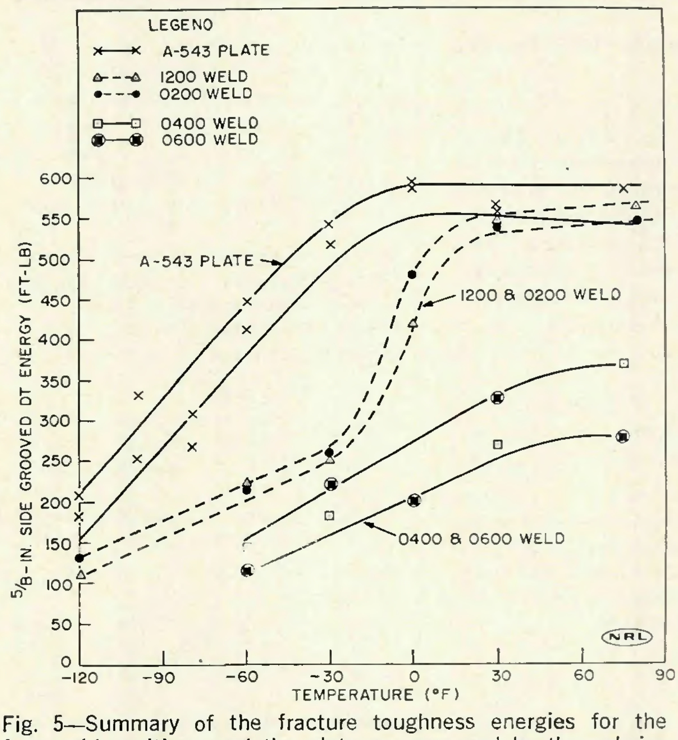

Fig. 5—Summary of the fracture toughness energies for the four weld positions and the plate as measured by the subsize DT test

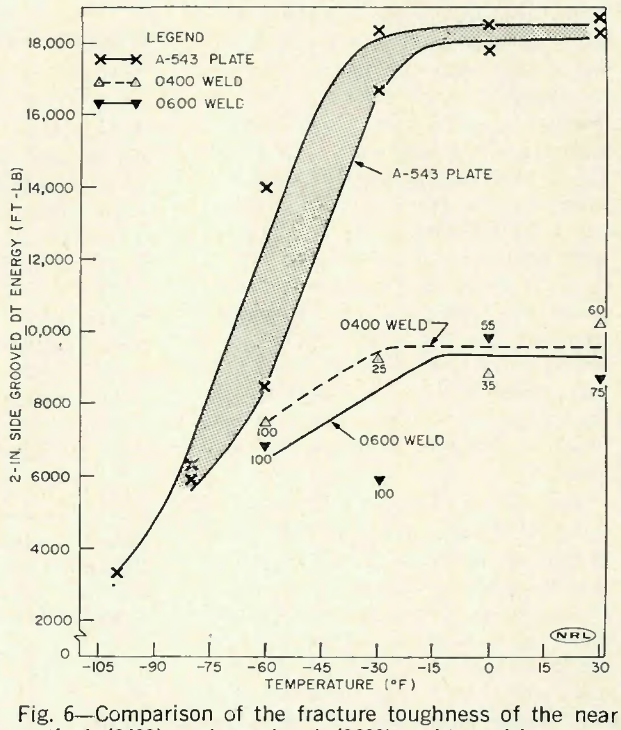

Fig. 6—Comparison of the fracture toughness of the near vertical (0400) and overhead (0600) weld positions with that of A-543 plate using the full-thickness (2 in.) DT specimen. The results corroborate conclusions deduced from subsize DT tests. The number labels on the symbols indicate the percentage of fracture in the weld metal

gy values is evident between the A-543 plate and the weld metals representing the flat (1200) and the almost vertical (0200) welding positions. Both of these weld metals absorbed less energy in the fracture process than did the A-543 plate at a given test temperature within the transition temperature range. The temperature transition drops off from the upper shelf in weld metal from both positions at about 20° F, whereas the plate is still on the upper shelf at —30° F.

The fracture toughness curves of the 0400 and 0600 weld metals are compared with A-543 plate in Fig. 4 from the data of Table 3. It is evident that the fracture energies required to propagate a crack through either the almost vertical 0400 or the overhead 0600 weld metals are considerably less than that needed for the plate at all test temperatures investigated. The upper shelf energy values for 0400 and 0600 weld metals were approximately half the shelf level energy of the A-543 plate. The scatter in the data from the weld metal specimens is expectedly greater than that from plate specimens due to the greater number of inhomogeneities normally occurring in weld metal.

A summary of the relationship between the fracture energies of the four weld metal positions and that for the A-543 plate is presented in Fig. 5. It is evident that the data band for the 0400 and 0600 welds has entirely different characteristics from either the band for the 1200 and 0200 welds or the band for the plate. The transition of the latter two bands is rather abrupt from the upper shelf region, in which crack propagation is governed by gross strain to the low temperature region, in which linear elastic conditions prevail. The transition is gradual for the data band of the 0400 and 0600 welds, and the fracture appearance of these specimens indicates that the 300 ft-lb shelf is in a region in which crack movement is governed by elastic-plastic conditions rather than gross strain conditions.

The full-thickness (2 in.) DT test was employed to develop the characteristic fracture mode and to measure the energy of the fracture process under the more severe conditions of a thicker section. The size of the full-thickness specimen and limited material for the investigation precluded extensive full-thickness DT evaluations. The averaged full-thickness data values are reported in Table 3, and Fig. 6 indicates the change in fracture energy with temperature for the 0400 and 0600 weldments and the A-543 plate. The relative positions of the upper shelf for the plate and weldments is similar to that indicated by the subsized $^5/_8$ in. DPN-DT data of Fig. 4.

For both the full-thickness and the subsize toughness tests, the fracture energy indicated by the upper shelf region of the plate was twice as high as the upper shelf energy of the welds. The full-thickness DT shelf values (Fig. 6) were 18,400 ft lb for the plate vs. 9400 ft-lb for the 0400 and 0600 welds, and the subsized $^5/_8$ in. DPN-DT tests (Fig. 4) measured 570 ft-lb for the plate and 300 ft-lb for the welds. The temperature of transition from the upper shelf for the A-543 plate was the same for the two fracture toughness tests (—20° F); however, there was a significant difference in this temperature from the two tests for the 0400 and 0600 weldments.

The restricted width of the narrow-gap weldment was found to have a considerable influence on fracture toughness. Since the plastic zone size increases with temperature, a temperature was reached at which the *fracture plane* of even the side-grooved specimens deviated from the weld and propagated into the plate metal. This resulted in a rapid increase in the energy required to extend the crack, since the plate was significantly tougher than the weld metal. The numbers next to the data points in Fig. 6 indicate the percent of the fracture surface composed of weld metal. For the 0600 weld the percent of weld metal on the fracture surface fluctuated from 100 to as low as 55% as the temperature is increased. A similar trend is noted for the 0400 weldment.

Although the side grooves were effective in eliminating the shear lips in full 2 in. thick test specimens, they could not prevent the plastic region (enclave) associated with the crack front from extension into the base metal at the higher temperatures. The side-grooved specimens indicated the influence of temperature on toughness in two ways. As the temperature and therefore the toughness increased, lateral contraction became increasing-

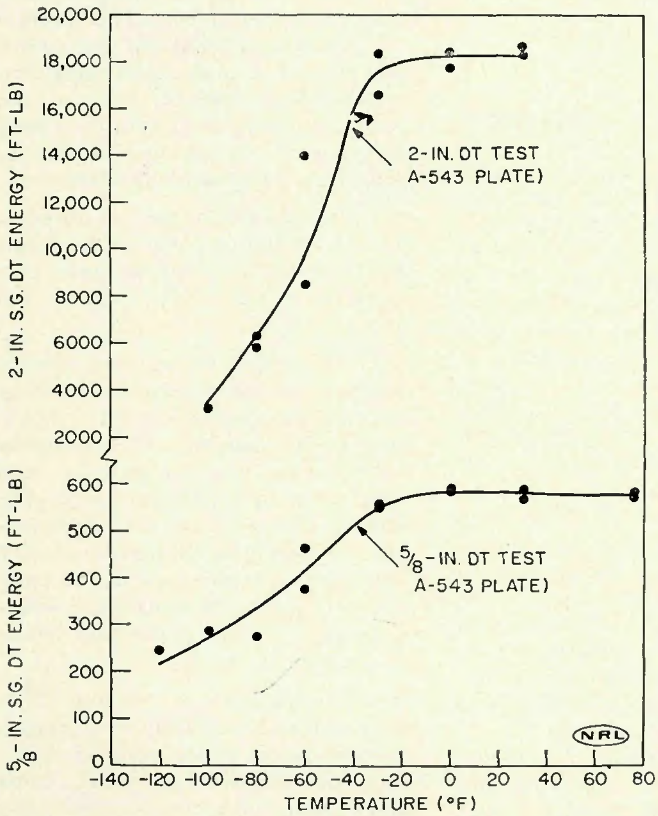

Fig. 7—Comparison between 2 in. thick DT test results and subsize DT test for A-543 plate material. The transition temperature is similar for the two tests

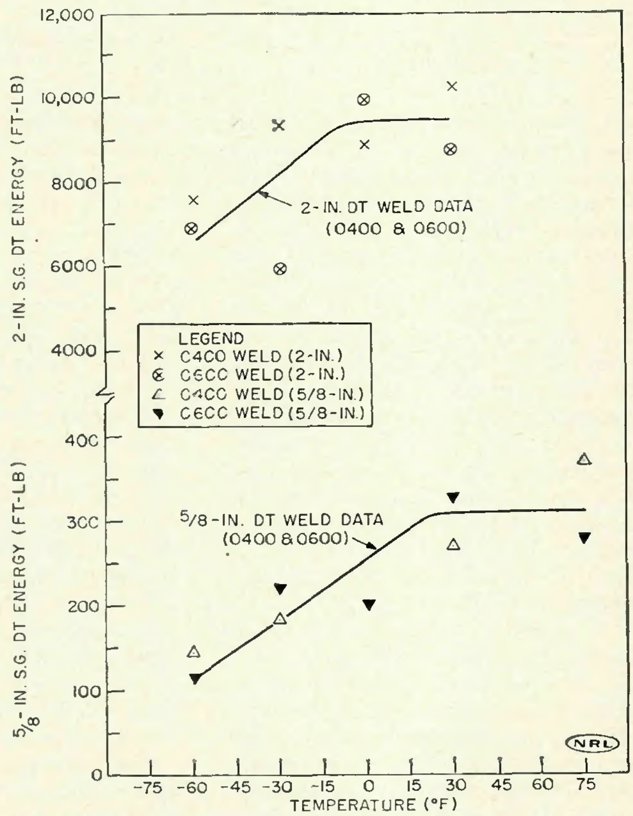

Fig. 8—Comparison of full-thickness and subsize DT test data for 0400 and 0600 welds

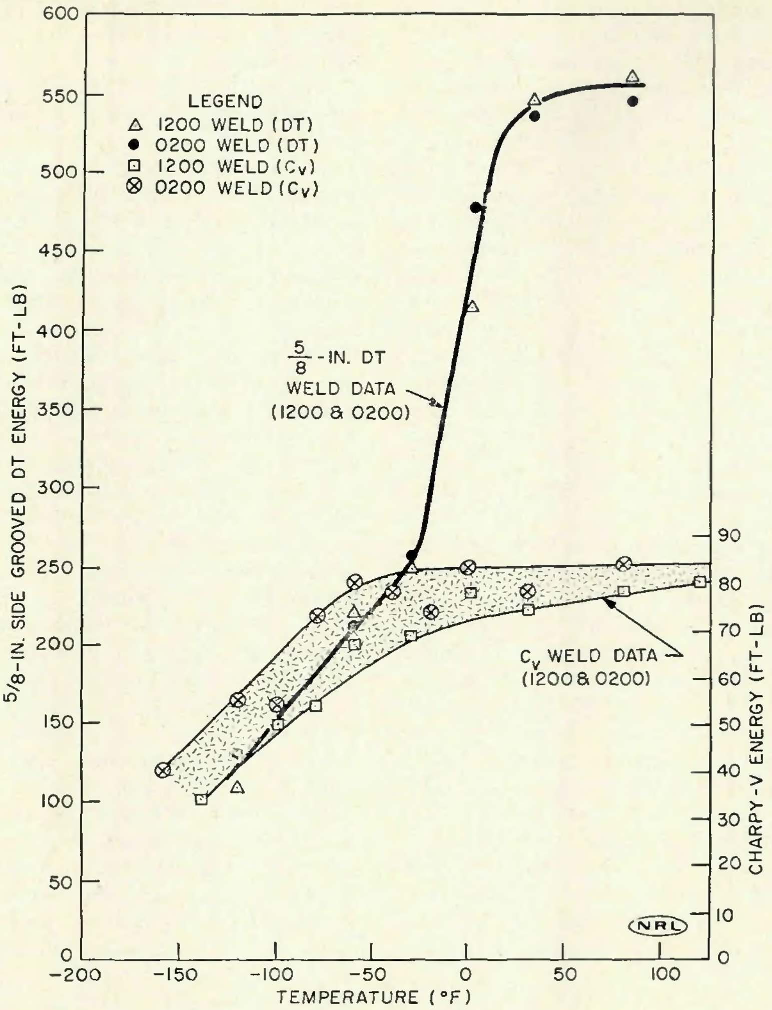

Fig. 9—Comparison of subsize DT test transition with C_v transition for 1200 and 0200 weld data

ly evident on either side of the fracture plane. At the same time, the fracture surface changed from a planar surface to one which became concave on one specimen half and convex on the other. The degree of convexity increased with toughness; since the nominal $^1/_4$ in. weld width was restrictive, the center of the fracture surface breached the base metal, increasing the measured DT toughness of the specimen in proportion to the amount of A-543 plate that became involved. The increase of the plastic zone size with temperature and the resultant divergence of the fracture from the weld is a major and previously unrecognized attribute of this welding method.

A comparison between the full-thickness DT test and the subsized DT test is drawn in Fig. 7 for the A-543 plate. As was noted before, the temperature at which the transition from the upper shelf begins is remarkably similar for the two tests. The temperature of deviation from plane strain to plane stress (rise in energy noted) is also the same. The fact that the temperature transition of dynamic fracture toughness is essentially independent of section size has been demonstrated by other NRL investigations for DT specimens with thicknesses ranging from $^5/_8$ in. to 6 to 12 in.[4] Thus, the smaller volume $^5/_8$ in. specimen with its pressed notch may be substituted for the bulkier 2 in. thick specimen with the electron-beam weld without any loss in the definition of the toughness transition of the plate. A comparison of the same two fracture toughness tests in Fig. 8 for 0400 and 0600 weld metal indicates an apparent 25° F difference in the initiation of the transition drop from the upper shelf. However, the limited number of tests and scatter due to nonuniform distribution among the test specimens of inhomogeneities commonly present in weld metals do not permit exact definitions or differences, if any. We are of the opinion that the difference is negligible.

The subsize DT results are plotted against the C_v values for 1200 and 0200 welds in Fig. 9. The C_v test does not appear to discriminate as selectively as does the $^5/_8$ in. DT. The DT transition from the upper shelf is sharp and distinct compared with the more gradual transition evidenced by the C_v data. There is a considerable difference between the two curves in defining the temperature at which the upper shelf transition begins. At −40° F the C_v curve indicates upper shelf performance, implying that the fracture process is governed by gross strain criteria. The subsized DT shows, however, that the upper shelf does not commence until the temperature rises to 60° F. Indeed, at −40° F, crack extension in the sharply notched $^5/_8$ in. DT would be influenced by elastic-plastic or linear elastic conditions as evidenced by the fracture appearance. This exemplifies the important role of notch sharpness and mechanical restraint in the fracture process. The C_v test is inadequate in these respects and leads to incorrect engineering conclusions regarding the fracture mode propagation features of the metal. On the other hand the DT test satisfies the required conditions and provides proper definitions of the fracture mode.

Conclusions

1. The subsized DT test results indicate that the upper shelf (full ductility) toughness level of the 1200 and 0200 narrow-pap process weldments is equivalent to that of A-543 plate; however, the transition drop from the shelf begins at a much higher temperature in the weldments. The subsized DT data for the 0400 and 0600 welds demonstrate a shelf level toughness approximately one-half that of the plate; the upper shelf transition drop occurs at a temperature similar to that of the 1200 and 0200 weldments.

2. The data from the full-thickness (2 in.) DT test corroborate the results and conclusions deduced from performance of the subsize ($^5/_8$ in.) DT test.

3. The subsize DT test data provide accurate and inexpensive definition of the fracture toughness transition, obviating the necessity of conducting full-thickness tests for plate or weld material in this thickness range. The general character of the weldments are also described by the subsize DT test, especially in regard to the characteristic mode of dynamic fracture propagation, which is the limit severity condition in service.

4. Comparisons of $^5/_8$ and 2 in. thick DT tests featuring side grooves disclose unique plastic zone size characteristics of narrow gap welds. These observations are of major engineering importance to concepts of narrow gap weld joint designs. The observations are in agreement with fracture

mechanics theory relating to plastic zone parameters as a function of increasing fracture toughness. The integration of the possible variations in weld metal toughness properties as a function of welding position (flat, vertical, or overhead) require consideration of the special features of N-G welds.

5. The C_v test is misleading in its indication of the temperature range at which gross strain governs the fracture process. In effect, it suggests retention of full ductility fracture toughness for temperatures at which the DT test clearly demonstrates essentially flat fractures of low fracture toughness. The dangers of basing weld metal fracture toughness conclusions on C_v data (without corroboration by other test methods) are apparent from these studies. This is but another manifestation of the unreliability of the C_v test which applies to base metal as well as weld metals.

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