Characterization of Fracture Toughness of 5Ni-Cr-Mo-V Steel by Charpy V-Notch and Dynamic Tear Tests

Use of the Charpy test is complicated by difficulties of energy value interpretation, while the dynamic tear test provides for a choice of specification criteria for assessing fracture toughness

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ABSTRACT. Representative samples of 5Ni-Cr-Mo-V steel in the product forms of plate and weld metal were investigated with respect to fracture toughness characterization features provided by the Dynamic Tear and Charpy V-notch tests. The intrinsic fracture propagation features were defined by the energy-temperature relationships obtained with the dynamic tear (DT) test.

The fracture modes of both base metal and weld metal as defined by the DT test demonstrated sharp transitions in fracture toughness with temperature. In contrast, the fracture modes of the C_v test remained essentially unchanged and the energy curves had shallow, indefinite slopes. A very high degree of scatter for the C_v energy values was observed for weld metal. The scatter was attributed to the inherent metallurgical differences found in multipass weldments and the small sampling size in the C_v test.

The DT test method provides for a choice of specification criteria for assessing the fracture toughness of these materials based on a DT energy value at a single or several temperatures. The choice of specific criteria depends on the reference aims as relating to properties involving the transition region or the shelf level. Procedures for establishing significant C_v test criteria are described. In general, the use of the C_v test is complicated by difficulties of interpretation of energy values relating to the transition region and the shelf.

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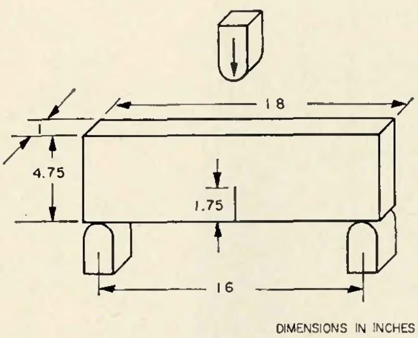

Fig. 1—Schematic of 1 in. dynamic tear (DT) test specimen

Introduction

A primary consideration in the design of large, welded structures is the prevention of catastrophic failure. This requires the establishment of an accurate sampling method and a definitive testing procedure for the material involved. Although potential catastrophic failure is by no means the designer's only problem, it is a constantly recurring question that arises when new materials and welding processes are introduced.

The standard Charpy V-notch (C_v) test has provided convenient and reliable procedures for the assessment of fracture toughness of conventional as-rolled or normalized structural steels. The popularity of the C_v test for specification and quality control was attained by virtue of its small specimen size and the apparent simplicity of specimen preparation and testing procedures. However, the use of the C_v test for establishing desired levels of fracture resistance of a material in a structure requires correlation with more definitive fracture tests which more closely model service conditions. These include specimens of relatively large sections, featuring sharp notches which provide interpretation to validated design models such as the Fracture Analysis Diagram (FAD).[1-3]

FAD design procedures are indexed to the NDT temperature, and al-

Table 1—Compositions of 5Ni-Cr-Mo-V Base Metals and Weld Metals, %

Code	C	Mn	P	S	Si	Ni	Cr	Mo	V	Ti	Cu	Remarks
Specification	0.12 max.	0.60–0.90	0.010 max.	0.010 max.	0.20–0.35	4.75–5.25	0.40–0.70	0.30–0.6	0.05.0.10	0.02 max.	0.15 max.	
Base metals:												
K-79	.11	.77	.005	.004	.25	4.72	.63	.52	.06	.00	.07	
K-86	.10	.78	.006	.004	.20	4.72	.65	.55	.06	.00	.07	
K-94	.12	.78	.006	.003	.20	4.75	.63	.55	.06	.00	.07	
Weld metals:												
K-81	.09	1.26	.005	.006	.24	2.41	.71	.82	.02	.00	.07	GMA
K-96	.09	1.55	.006	.003	.38	1.94	.99	.54	.03	.00	.07	GMA
K-94	.11	.65	.005	.003	.31	4.66	.66	.51	.02	.00	.09	GMA
K-83	.09	1.68	.003	.004	.36	1.65	.76	.46	.03	.00	.05	SMA
K-85	.07	.184	.007	.004	.40	2.18	.82	.56	.03	.00	.05	SMA

though the C_v test cannot define NDT temperature directly, a C_v energy level corresponding to NDT conditions for the conventional structural steels can be established by correlation. In essence, the C_v test serves as a reasonably reliable, secondary fracture toughness test when it is referenced by other, more definitive test methods.

For the conventional structural steels, the NDT temperature coincides with the toe or other regions of the C_v transition curve where the energy values change rapidly with the temperature. Although a different reference C_v energy value may be required, depending upon the steel's response to the mechanical conditions of the C_v test, a C_v energy may be established which corresponds to the NDT temperature as long as NDT occurs in the transition range. For steels involving a quench and temper (Q&T) heat treatment, the C_v energy—NDT reference may occur at high energy levels. In fact, for some Q&T steels, the NDT coincides with the upper shelf.[2,4] Recognizing that new criteria would be required for such materials as well as for materials that do not feature a temperature transition, the dynamic tear (DT) test was evolved as a practical engineering test for generalized characterization of fracture toughness, suitable for a wide variety of metals.[5]

The DT test was designed as a limit severity test with respect to notch sharpness, dynamic loading, and

Table 2—Tensile Properties of 5Ni-Cr-Mo-V Base Metals and Weld Metals

Code	YS,[a] ksi	UTS,[a] ksi	RA,[a] %	El,[a] %	Remarks[b]
K79	136.9	144.4	64.4	19	Base metal
K86	132.0	140.7	60.4	17.9	Base metal
K94	143.1	152.7	58.3	16.5	Base metal
K81	140.8	147.2	63.8	18.8	GMA weld metal
K96	143.5	149.0	61.9	17.5	GMA weld metal
K94W	135.2	145.4	61.2	16	GMA weld metal
K83	145.9	150.3	63.5	14	SMA weld metal
K85	146.9	151.7	57.6	18	SMA weld metal

[a] YS—yield strength; UTS—ultimate tensile strength; RA—reduction in area; El—elongation.
[b] GMA—gas metal-arc; SMA—shielded metal-arc.

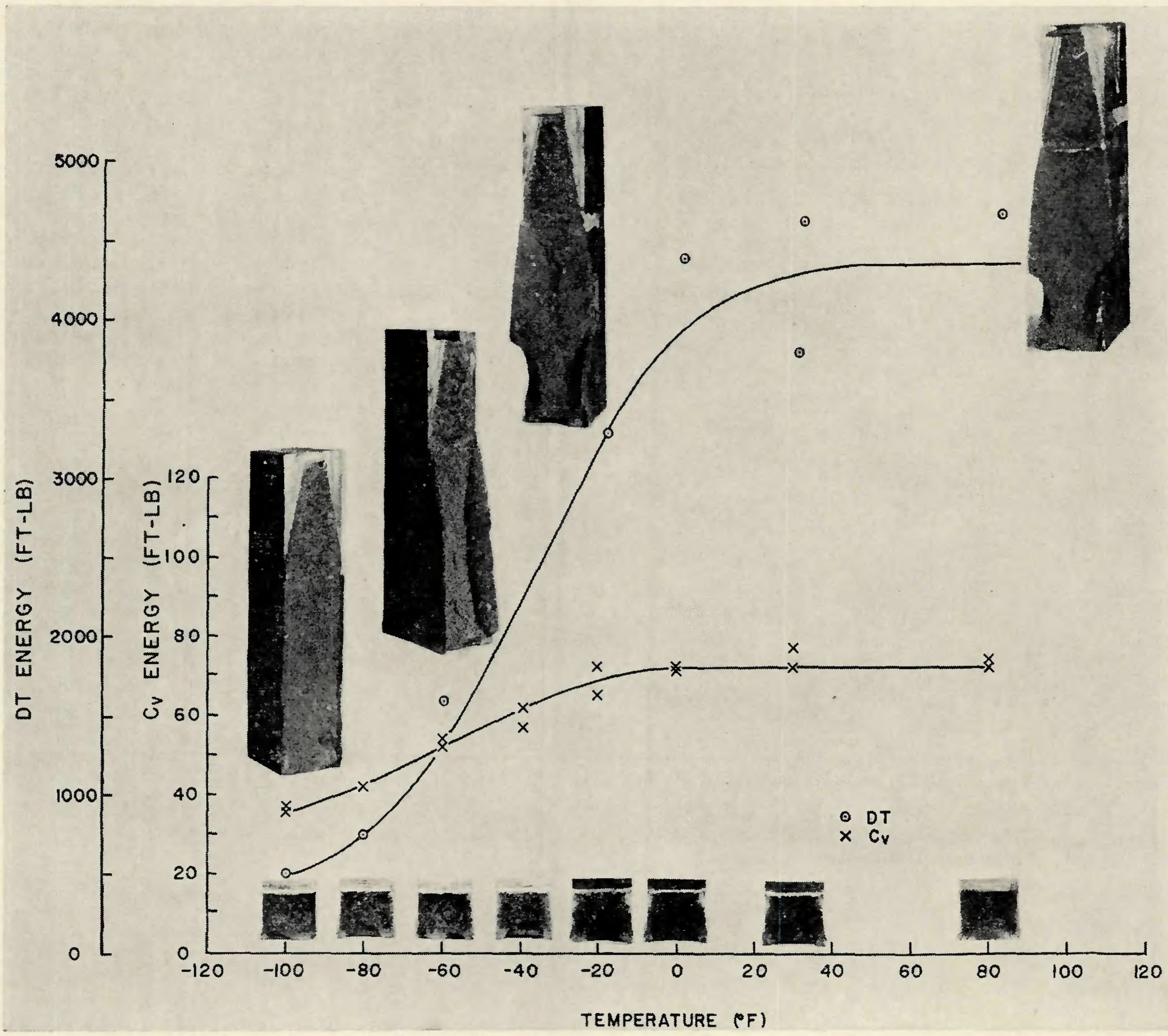

Fig. 2—Dynamic Tear (DT) and Charpy-V temperature transition for 1 in. 5Ni-Cr-Mo K-94 plate. Note the corresponding increase in shear-lip and fracture energy with increasing temperature for the DT test. There is very little change in the fracture appearance for the entire temperature range for the C_v test.

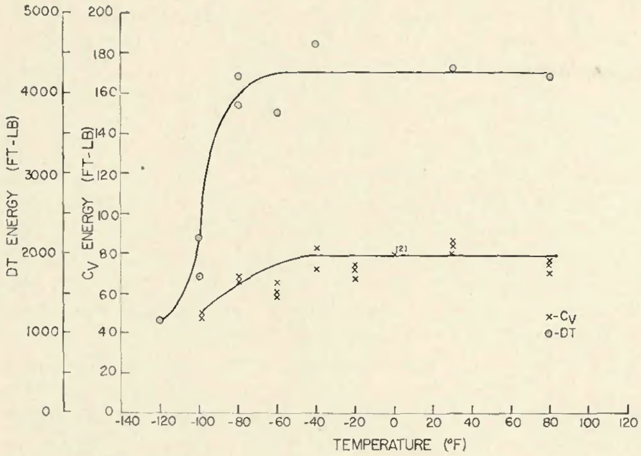

Fig. 3—Dynamic Tear and Charpy V-notch test data for 1 in. 5Ni-Cr-Mo-V plate K-79

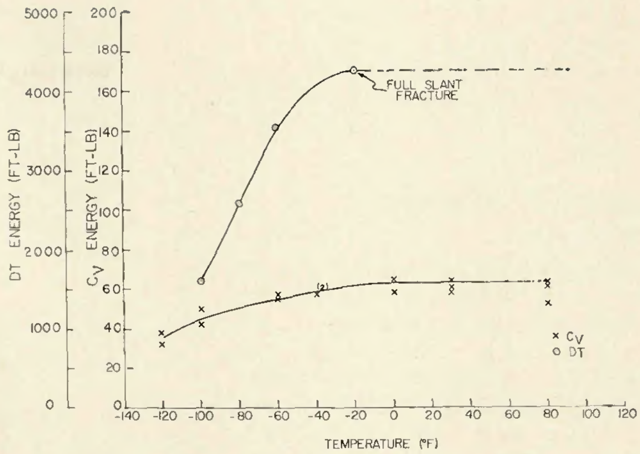

Fig. 4—Dynamic Tear and Charpy V-notch test data for 1 in. 5Ni-Cr-Mo-V plate K 86

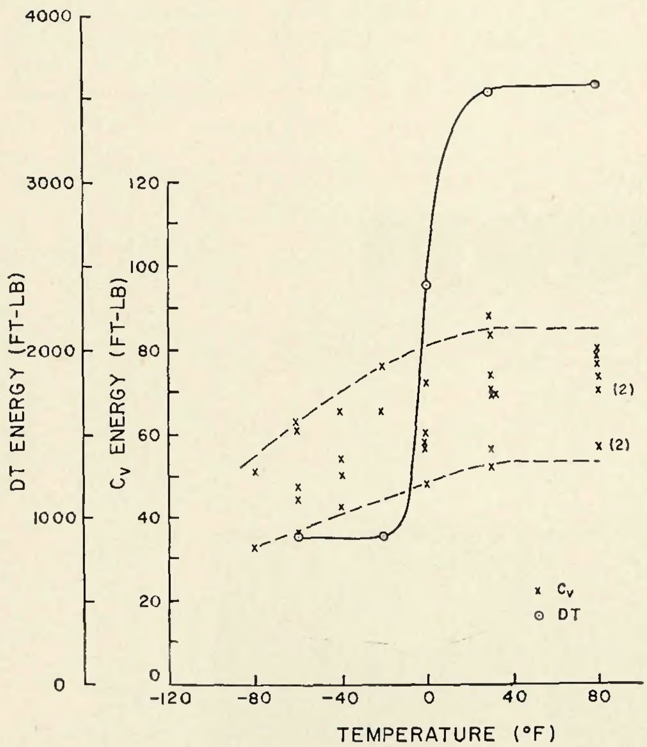

Fig. 5—A comparison of the fracture toughness transition as indicated by the Dynamic Tear and Charpy V-notch tests for gas metal-arc weldment K-96.

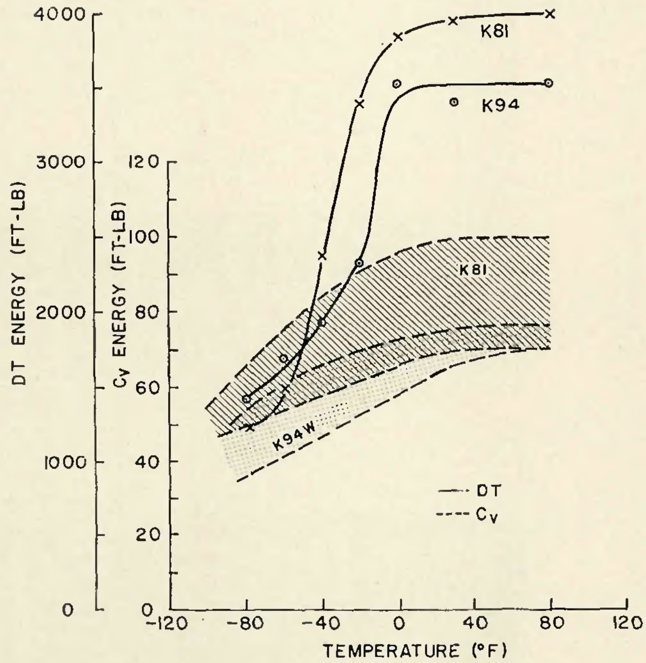

Fig. 6—Transition features of two gas metal-arc weld metals as indicated by Dynamic Tear and Charpy V-notch tests

mechanical constraint effects, i.e., the worst mechanical condition. A schematic illustration of the 1 in. DT test specimen is shown in Fig. 1. In the DT test, the material displays its intrinsic fracture modes as a function of temperature. The energy required for fracture propagation in the various modes represents a most important material property. Recently, a coupling was evolved between DT energy and fracture mechanics test values in the low energy range where elastic fractures occur.[4] The structural interpretation inherent to the DT energy values also provides for correlations with the C_v energy values related to upper shelf levels. In effect the C_v test is calibrated by extensive correlation data of this type. This paper presents data relating to performance criteria of the new HY-130T steel of 5Ni-Cr-Mo-V composition and its companion weld metals in the DT and C_v tests. The comparisons indicate serious difficulties in establishing reliable C_v criteria for the performance of this new structural metal.

Materials and Test Procedures

Three samples of 1 in. thick plate material and five welded samples of 5Ni-Cr-MoV steel were included in this investigation. The filler metal for four of the weldments was of nominal 2Ni-2Mn composition and the other filler metal composition was nominally 5Ni-Cr-Mo. Three of the weldments were made by the gas metal-arc process; the other two weldments were made by the shielded metal-arc process. Chemical compositions of plates and weld metals are listed in Table 1; tensile properties are listed in Table 2. NRL Code numbers are used to identify individual plates and weldments as shown in the tables.

Fracture energies of all the test materials were determined by the standard Charpy V-notch and the 1 in. DT tests. Samples for the C_v tests were taken from locations near each plate surface for both base metal and weld metal deposits. The tests were conducted over a temperature span ranging from —120 to 80° F. DT tests were conducted over the same temperature range in the weak (WR) fracture orientation for both plates and weld metals.

Discussion of Results

Base Metal

Results of both C_v and DT tests for the three samples of HY-130T plate material are presented in Figs. 2–4. In general, the C_v data for all three samples evidenced a limited and indistinct temperature transition curve, though in each case a leveling off to an upper shelf was observed. In contrast, a sharp transition of fracture toughness with respect to temperature for each sample of plate material was obtained with the DT test.

The fracture toughness transition for the K-94 material as defined by the DT test is shown in Fig. 2. The fracture appearance of the DT specimens corresponds to the rapid rise in DT energy in the transition region from 800 ft-lb at —80° F to a high upper shelf value of 4300 ft-lb at 0° F. The "flat" fracture (Fig. 2) at the "toe" region of the transition is indicative of brittle behavior of the material at that temperature. With increasing temperature the characteristic fracture mode becomes progressively tougher as illustrated by increases in the amount of shear lip developed on the fracture surface. An intermediate toughness level (50% shear at —60° F) and a full-slant, upper shelf toughness level are also illustrated by the appearance of the fractured DT specimens in Fig. 2.

The C_v test performance of the K-94 sample of 5Ni-Cr-Mo-V steel is also shown in Fig. 2. The C_v energy transition exhibits a very gradual slope. There is very little change in the C_v fracture appearance over the entire temperature span from —100° F to 80° F. Clearly the C_v test provides very limited definition of transition effects for this high strength quenched and tempered steel.

The same trends described for the K-94 sample of HY-130T steel are evident for two different heats of this 5Ni-Cr-Mo-V steel coded K-79 and K86, as shown in Figs. 3 and 4, respectively. The K-79 material, Fig. 3, manifests a very sharp temperature transition as defined by the DT test in comparison to the shallow, indistinct transition indicated by the C_v test. The transitions described by the DT energy curves clearly indicate a change in the characteristic fracture mode from brittle, elastic fracture at the "toe" region of the transition to full shear, high-energy fracture requiring gross plastic strain at the upper shelf. The DT transition signifies that a dramatic change in the fracture toughness of the metal is to be expected for struc-

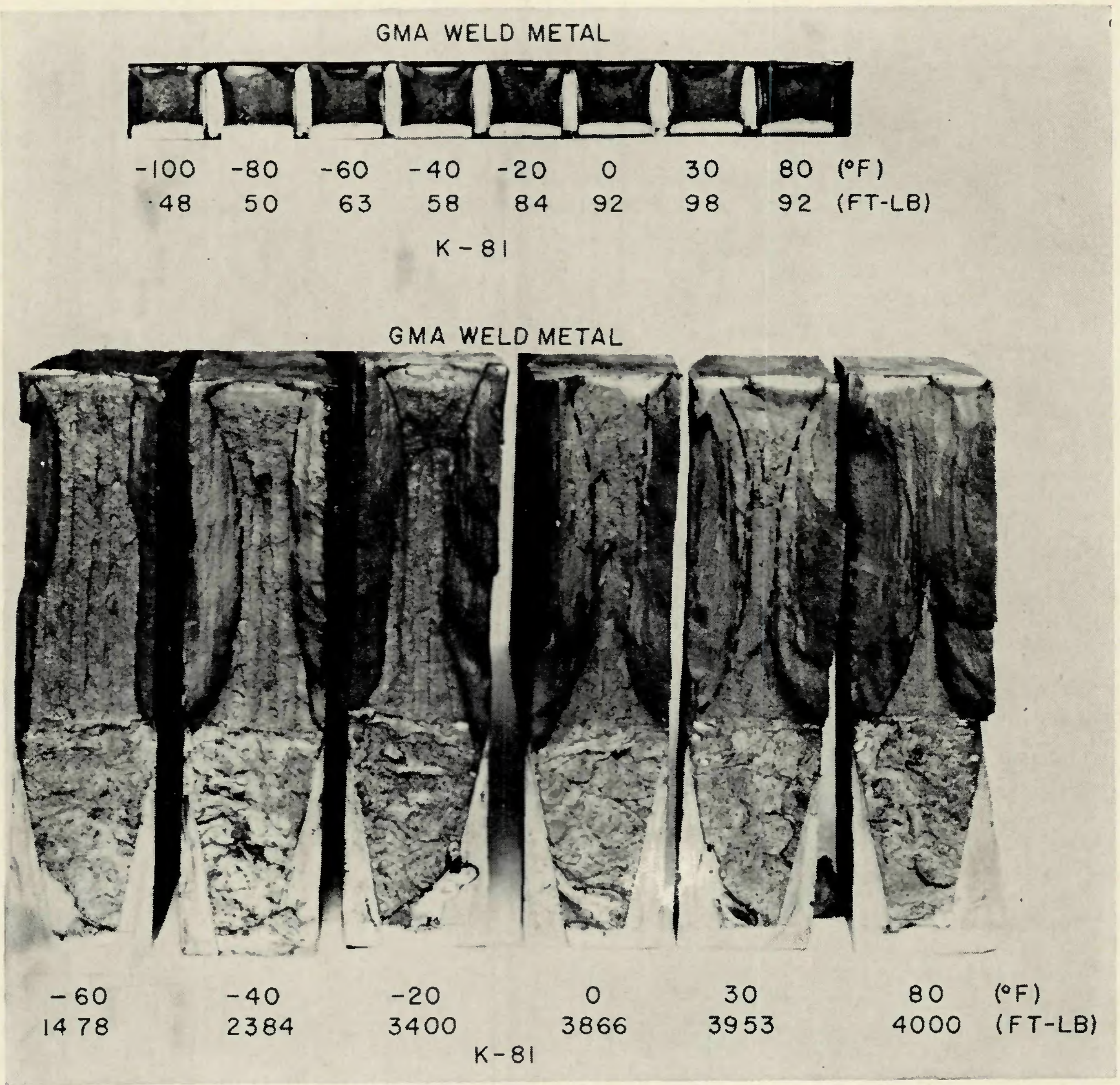

Fig. 7—Illustration of the lack of fracture mode transition of Charpy V-notch specimens (top) and the dramatic change shown by the Dynamic Tear specimens (bottom) for gas metal-arc weldment K-81

tural applications covering the respective temperature range.

Detailed definition of the predicted structural performance in the presence of flaws may be obtained from the Fracture Analysis Diagram (FAD) for temperatures in the lower portion of the DT test transition region. The Ratio Analysis Diagram (RAD)[4] applies to temperatures in the upper or shelf portion of the transition.

Variations of the transition temperature region are evident from the positions of the DT energy curves for the three plate samples. These variations would not be as evident if only C_v data were available since the transsition region is not as sharply defined with the C_v test.

Weld Metal

The results of the DT and C_v tests for weld metal samples are presented in Figs. 5–9. The performance features of these weldments were similar to that noted for plate materials, i.e., shallow C_v curves indicating little temperature transition effect and sharp, well-defined transitions indicated by DT energy curves. An equally important observation is that the scatter of the weld metal C_v data was much greater than that of the plate material.

The data for gas metal-arc weld metal sample K-96, Fig. 5, show a particularly sharp DT energy transition, 900 ft-lb at —20° F to 3600 ft-lb at 30° F. In contrast, the C_v energy scatter band for this material shows a low-slope, indefinite temperature transition, 40 ft-lb average at −80° F to 70 ft-lb average at +30° F.

The two other gas metal-arc weld metals coded K-81 and K-94, evidenced the same pattern of performance in the C_v and DT tests as K-96 weld metal—Fig. 6. Fracture surfaces of C_v and DT specimens for gas metal-arc weld metal (K-81) are compared in Fig. 7. The shear lip formation, outlined by dashed lines on the DT specimens, illustrates the usual distinct transition in characteristic fracture mode in the DT test. No visual evidence of change in fracture mode could be found from examination of the C_v specimens.

The DT energy transitions for the two shielded metal-arc weld metals in this study, Fig. 8, were not completed, because sufficient material was not available for tests at temperatures corresponding to full shelf level conditions. However, the performance of these two materials in the temperature span investigated, −40 to 80° F, is similar to those observed for base metals and gas metal-arc weld metals. The steeply rising DT energy curves indicate a distinct temperature transition. The broad C_v data bands for the shielded metal-arc weld metals were similar in shape to the C_v data bands for the gas metal-arc weld metals. However, the average shelf values were significantly lower—43 and 60 ft-lb for K-85 and K-83 respectively—indicating fracture characteristics that were inferior to the gas metal-arc weld metals.

The high degree of scatter observed in the C_v energy curves for both gas metal-arc and shielded metal-arc weld metals is not unexpected from consideration of the size of the C_v specimen in relation to the metallurgical variations in multipass welds. Different cooling rates and multiheat treatment from successive deposits of weld metal are responsible for these variations. The small size of the C_v specimen limits the characterization of fracture toughness to few, successive weld metal layers. Such scatter was not evident in the DT energy curves for weld metals because the full-thickness DT specimen integrates these differences into an overall assessment of the fracture toughness of the weldment. The larger sample size of the DT test therefore provides an integrated criteria of performance which is representative of structural performance of the full thickness weld.

Summary

The data from the three plate samples of 5Ni-Cr-Mo-V steel and the five corresponding weld metals included in this investigation, provide conclusive evidence of major significance to engineering design and specification procedures. The salient points may be outlined as follows:

1. HY-130T steel in the product forms of plate and weld metal feature sharp temperature transitions in fracture toughness. High levels of fracture toughness are obtained in the upper shelf region.
2. Fracture Analysis Diagram concepts can be utilized to define structural performance criteria for materials with high upper shelf fracture toughness levels. FAD concepts require accurate determination of an index point in the transition region.
3. The DT test accurately characterizes the temperature transitions of the HY-130T plate and weld metals. The DT energy curve provides the desired sharp transition features required for indexing to the FAD.
4. The insensitivity of the C_v test to the temperature transition of HY-130T plate and weld metals seriously complicates the use of this test for defining fracture toughness criteria at any toughness level below the upper shelf.
5. The shelf performance of HY-130T base plate material can be analyzed by C_v test methods only if the test procedures clearly ensure that the measured values relate to shelf condi-

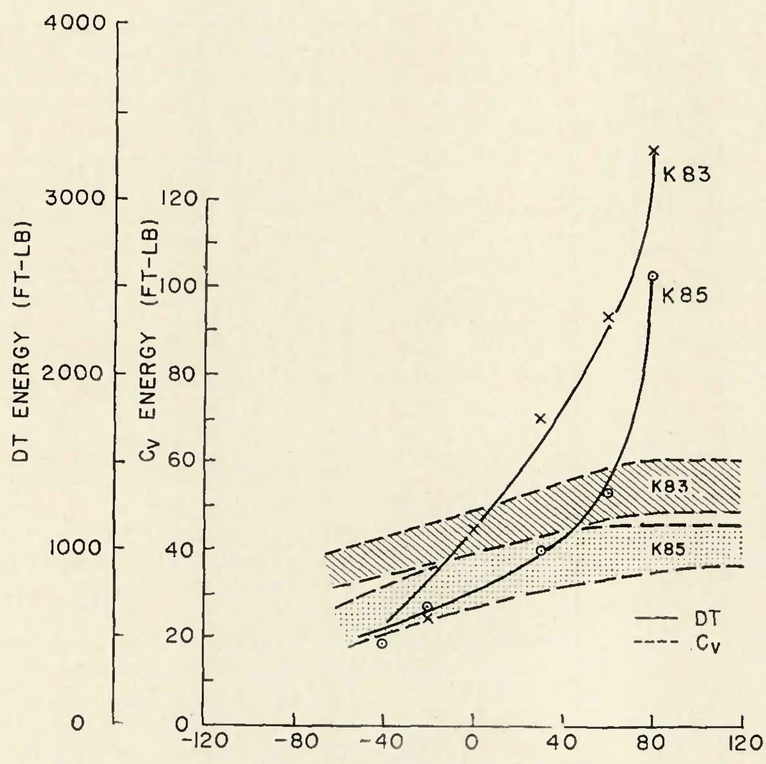

Fig. 8—Dynamic Tear and Charpy V-notch test temperature transitions for shielded metal-arc 5Ni-Cr-Mo-V weld metals

tions. Tests conducted at two significantly separated temperatures may be used to provide confidence that shelf values are measured. For this purpose, the C_v values at the higher temperature should be reasonably similar to the values defined at the lower temperature.

6. The high degree of scatter noted in certain weld metal C_v energy curves seriously limits the usefulness of the C_v test by any procedure that may be devised.

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