EFFECT OF ROLLING PRACTICE AND MICROSTRUCTURE ON THE NOTCHED-BEND FRACTURE TRANSITION OF STEEL

by

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ABSTRACT

A study has been made of the grain-size dependence of the ductile-to-brittle transition temperatures of conventional- and controlled-rolled steel plates. The transition temperatures have been determined relative to several criteria by the notched slow-bend test of van der Veen. The different grain sizes were obtained by various annealing and normalizing heat treatments and the accompanying changes in microstructure were also noted. Grain sizes were measured by lineal analysis.

Increasing the grain size had the effect of raising the transition temperatures, as expected from earlier work. In the range from 8.5 to 6.5 ASTM grain size number this dependence is almost linear and is about 20°C/ASTM number for both materials. Onwards from 6.5 to 4.5 ASTM grain size number the gradient gradually drops to about 10°C/ASTM number. The controlled-rolled plate shows a consistent improvement in notch toughness over the conventional plate--the extra-grain-size effect--by about 15°C, in terms of transition temperatures, irrespective of the grain size.

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I. INTRODUCTION

Controlled rolling is a recent trend in the hot rolling of steel plates at lower-than-normal temperatures with regulated temperature-reduction programs.[1] This practice results in an increase of the notch toughness over the conventionally rolled product. The improvement of the mechanical properties may be directly attributed to the structural changes produced by the different plastic-deformation history, yet a detailed explanation for this improvement still remains to be formulated.

Various micro- and sub-structural details control the notch toughness of a given material. However, many of these are of negligible importance in the range of structures under consideration. Ferrite grain size exerts a marked influence on the ductile-brittle transition and general investigations based on Charpy tests have been made of the dependence of transition temperature on ferrite grain size.[2-7] Steels of finer ferrite grain size have lower transition temperatures. In general, the relationship is very nearly linear and the decrease of transition temperature has been reported to range from 8 to 15^{o}C/ASTM grain-size number.

It is clear that an important reason for superior notch toughness in a controlled-rolled plate is the smaller grain size produced by such processing. However, there has also been indication of an extra-grain-size effect from measurements of Charpy V-15 ft.-lbs. transition temperature.[2] To evaluate this effect on the basis of fracture-appearance transition has been the main theme of the present work.

Fracture-appearance criteria, as a rule, give wider differentiation in transition between two steels than ductility criteria. This differentiation may be further increased and the transition made steeper by use of slow-bend tests. Van der Veen has shown that for two steels the difference in fracture-appearance transition by notched slow-bend test is about 40°C as against 23°C with ductility (energy absorbed) criterion of Charpy test.[16]

Presumably, the grain size of the structure being tested is significant rather than prior austenitic grain size. It is difficult experimentally to vary only the grain size and as is the case with similar results obtained earlier,[8] the changes in grain sizes may be accompanied by other changes in the microstructure. Therefore, before one could attribute any change in notch toughness to a given change in grain size, it is desirable to know the dependence of the notch toughness on other microstructural variables.

(Substructural effect) Mechanical fibering, commonly associated with ferrite banding and alignment in the direction of working of inclusions and other phases is a factor on which the notch toughness property has been thought to depend.[2] The presence of a fibre structure is expected to depress transition temperature only when fracture occure in the presence of triaxial stress with cracking across the fiber. As proposed by Soete[10] and Matton-Sjoberg,[11] tensile stress over the weakest plane may become sufficiently high to produce cracking or fissuring at right angles to the main crack path. This results in relieving the triaxiality which acts to elevate transition temperature.

Cleavage fracture in steel plates and structural members may be aided by multiaxial and unsymmetrical stress systems, imposed by various service conditions. It is natural that the test method of evaluating notch toughness should simulate at least some of the basic conditions of loading or stressing encountered in service. In the conventional tensile tests, the applied stress is uniaxial. In the notched cylindrical tensile coupon, although lateral stresses are induced by the presence of the notch, the cross-section of the coupon is symmetrical. The notched-bar impart test involves the factors of constraint and stress concentration to an important degree. However, the results are profoundly affected by local nonhomogeneity of the material tested and by the "mass effect", as it is necessary to use a 1-cm square cross-section bar to represent not only 1/2 in. bars but likewise material of much greater width and thickness. Moreover, the rate of loading is much higher than that for normal engineering structures. Most brittle failures have taken place under loading which is almost static. A notched-bend coupon of larger dimensions under slow loading would be considered suitable for this investigation.

One of the earliest slow-bend tests for evaluating toughness was the T-bend test proposed by Bibber.[12] Later, Cornelius and Fashel developed a notch bend specimen comprising a transverse bead weld with a parallel notched machined so that its apex touched the fusion line.[13] The specimen was bent around a pin until the first appearance of a crack at the root of the notch. Kommerell and Bierett suggested using an unnotched longitudinal bead weld and later modified this by having a notch across the weld bead to restrict the deformation.[15] The van der Veen test[16] used in this investigation shows much resemblance to Bagsar's DX-text;[14] however, it was developed independently by Dr. J. H. van der Veen of Royal Netherlands Blast Furnaces and Steelworks, and has minor differences with regard to notch-depth, procedure, and interpretation.

The van der Veen test coupons include full thickness of the plate; this takes care of the so-called "mass-effect" and does away with local nonhomogeneity. The fracture is made to propagate in the direction of rolling and perpendicular to the plate surfaces. This being the weaker direction yields a more conservative value of the transition temperature[14] and on account of anisotropy during rolling introduces some scatter in the results. The fracture propagation in the Charpy specimen is transverse to the direction of rolling and consequently these effects get reversed. These features of the test, including slow-bending, help to attain reasonable similarity to practice conditions, and this is reflected in the transition temperatures which are in the same range as service temperatures. Comparison with other tests have shown that with this test at least same degree of differentiation between different plates and at least the same steepness of transition curves is obtained as with Kommerell and Kinzel tests.[16] With impact tests, however, less differentiation is obtained and the width of the temperature-interval in which the transition takes place is found to be more than twice as large.

Slow bending makes possible the recording of load-deflection diagrams and thereby the measurement of various criteria for brittle fracture. Usually transition temperatures are determined on two bases--"ductility" and "fracture-appearance". The determination of the latter is facilitated by the minimum tendency to start cleavage at the neutral axis of the bar giving, consequently, a sharper transition. The evaluation of brittleness is based only on types of diagrams and fractures and not on absolute values of certain criteria, such as energy to fracture (as in Charpy tests). This is considered an important advantage of this test, because the tendency to start cleavage, determined in this way, is not confused with other properties of the steel, such as the tendencies to start and propagate fibrous fractures.

Criteria of Transition

Transition temperatures have been expressed in terms of the three criteria used by van der Veen: Temperatures at which (1) the mean depth of the fibrous area under the notch - termed "mm fibrous" - corresponds to 32 mm. (2) the ratio of the cleavage load to maximum load equals 0.7, the cleavage load being that at which cleavage fracture initiates with an audible report, and (3) the deflection at maximum load equals the mean of these deflections corresponding to fully ductile and brittle behaviors.

Criteria (1) and (2) are based on fracture appearance and are more or less equivalent, although the former is preferred because of a somewhat greater accuracy. Such a criterion is analogous to the 50% shear criterion in Charpy V-notch tests, and may be considered as a measure of the tendency to start cleavage from a fibrous crack propagating in material that has been slightly deformed in tension. Criterion (3) is based on ductility, and the central deflection of the bar at maximum load, Dm, is plotted against temperature and the transition temperature is the one which corresponds to the mean of the fully ductile and brittle behaviors; this transition could be appreciably affected by the notch geometry and is somewhat more difficult to determine on account of its continuous nature. All criteria refer only to the behavior of the bar up to the start of a cleavage crack and are therefore important for the study of the tendency to start cleavage fracture.

For fractures other than completely brittle, the incipient crack starts a little before the maximum load is reached and the fracture propagates in a fibrous manner from the notch up to a point and then changes suddenly into crystalline for the rest of its path. This type of fracture would as a rule not be obtained in notched tensile tests and may be considered to be typical for bend-tests. For completely brittle specimens the crystalline fracture starts immediately, at the root of the notch at or little above the yield-point of the load-deflection diagram and far before the point at which, according to observation, the fibrous incipient crack would otherwise have started. The various types of diagrams that are encountered are represented in Fig. (1) together with the corresponding fracture appearances.

Starting with the first type of diagram (Type a) which represents an entirely fibrous fracture, the others show a gradual increase in the brittleness of the steel, by decreasing testing temperature. After the initiation of the crystalline cleavage crack, a measurable amount of work is absorbed in most cases in spite of a subsequent crystalline fracture. The fracture surface then shows rather narrow shear-fractured edged bordering on the plate-surfaces. Sometimes these fibrous edges widen and join to form a so-called thumbnail of parabolic shape, or further lead to a sequence of alternate fibrous and crystalline areas in the fracture. This results in the so-called "tail" of the diagrams.

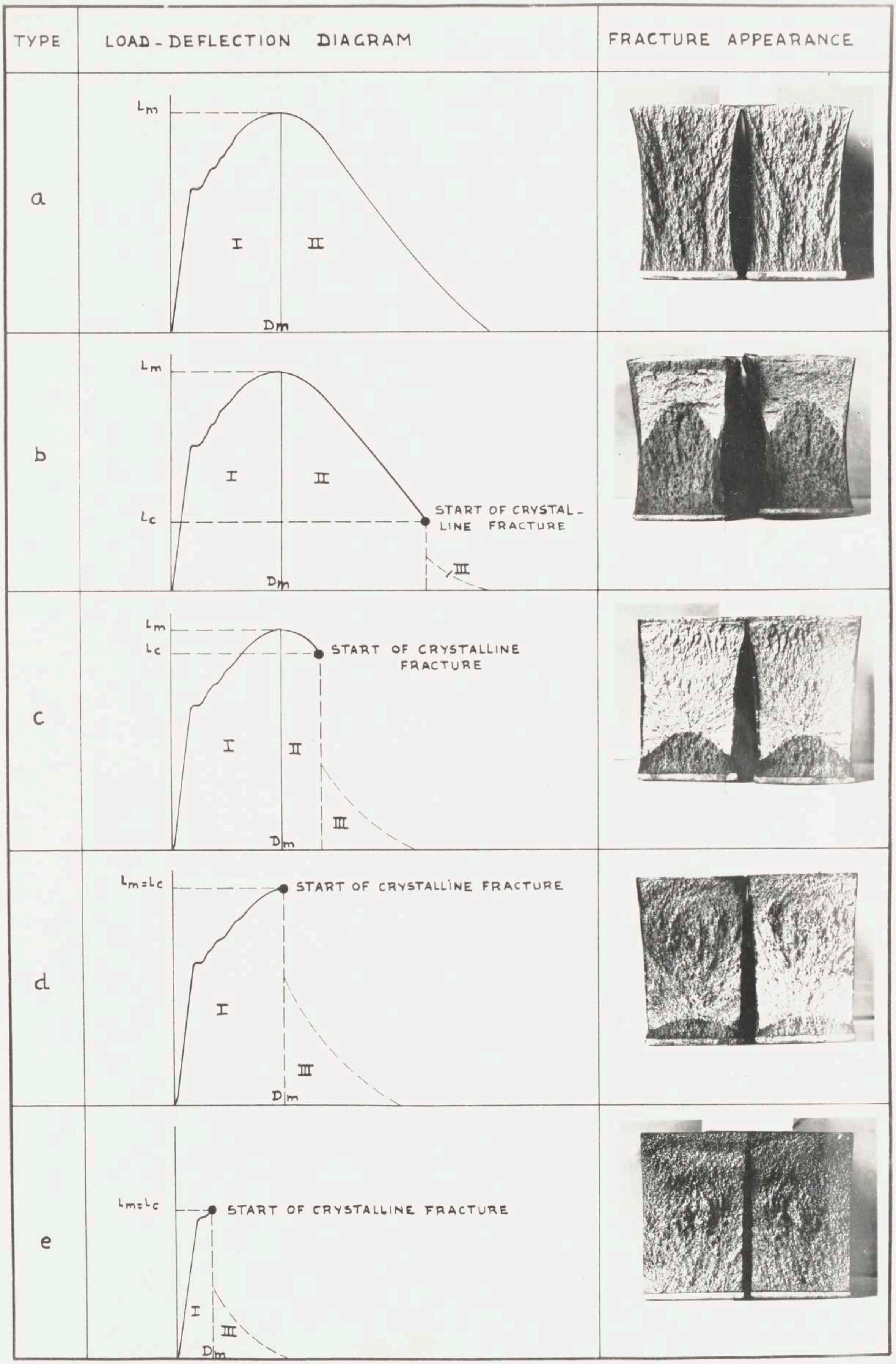

Fig. 1 - Representative Load-Deflection Diagrams with the Corresponding Fracture-Appearances.

II. APPARATUS AND EXPERIMENTAL PROCEDURE

2.1 Plate Material

The plates were produced by the Royal Netherlands Blast Furnaces and Steel Works, Holland. They were 1-1/2 in. thick and had a chemical analysis of:

C: 0.15

Mn: 1.18

Si: 0.03

P: 0.017

S: 0.026

Adjacent ingots were taken from the same charge and one was rolled in a conventional manner (designated S), while the other was controlled-rolled (designated C) with the last 30-35 percent of the reduction, comprising about 8 passes, in the two-phase region and with a finishing temperature of 720°C. The detailed rolling schedule is given in Appendix I.

2.2 Heat Treatment

The plates were heat treated in pieces of 9" x 25" and the different treatments were designated as A, B, C, D, E as shown in Table I.

TABLE I

DETAILS OF THE VARIOUS HEAT TREATMENTS

	Annealing Temp.	Annealing Time	Cooling details
A		as-received	
B	1650°F	1/2 hr.	Cooled in still air-normalized
C	1700°F	6 hrs.	Retort-cooled in exothermic atmos.
D	2100°F	6 hrs.	Cooled from 2100°F to 1450°F in 1 hr-45 min. Cooled from 1450°F to 1200°F at 1.8°F/min. in exothermic atmosphere

Normalizing refined the grain size in the conventionally (S) rolled plates only; however, it imparted a more banded equiaxed structure in both C and S, plates. The various annealing temperatures and times were based on trial heat-treatments as tabulated in Appendix II; these results confirm the parabolic relationship of grain growth vs. time. Annealing time of 6 hours was chosen since longer annealing time did not materially affect an increase in the grain size. Treatment C showed a further increase in the degree of banding and the grain size obtained was as expected. Treatment D gave a Widmanstatten structure and somewhat smaller grain size than expected. Treatment E was given a slower cooling rate, thus avoiding the Widmanstätten structure and giving a fairly big grain size.

2.3 Test Coupon

The dimensions of the test coupon were t x 70 x 225 m.m.(t = plate thickness, 1-1/2 in.) and these were saw-cut so that the longitudinal axis of the bar was perpendicular to direction of rolling. Mill scale is not removed. In the middle of one of the machined sides a sharp 3 m.m. deep, 45° V-notch was pressed within two hours before testing, the notch axis being perpendicular to the plate surfaces (Fig. 2). This was done by a knife-edge die block made of heat-treated high-speed steel and suitable guide jig to press the notch to the 3 m.m. depth (Fig. 3). The compression section of the testing machine was used for the purpose (Fig. 4). The knife-edge of the die block was prepared by careful grinding, and reground every 10 impressions. More reproducible results and sharper notch radii can be obtained by this method than by ordinary methods of machining.

The radius of notch measured in plate-centre was found to be about 0.004 m.m., using a newly ground knife, and its value is not materially affected by subsequent use up to about 10 impressions.

2.4 Test Apparatus and Procedure

The specimen is placed upright (70 m.m. dimensions vertical) on two supporting rolls spaced 200 m.m. (8 in.) apart, fixed to a common base-plate, with its flat sides perpendicular to the rolls, and the notch located on the tension side and directly opposite the loading roll (diameter of 60 m.m.) (Fig. 5). This assembly is held between the cross-heads of a hydraulic testing machine and the specimen is bent slowly with a cross-head velocity of 0.5 in. per min. (Figs. 6 and 7). The machine is a Baldwin Lima Hamilton make with 200,000 lbs. testing capacity. Figure 8 shows a dimensioned drawing of the test coupon and loading arrangement.

Fig. 2 - Test Coupon

Fig. 3 - Close-up View of Knife in Holder

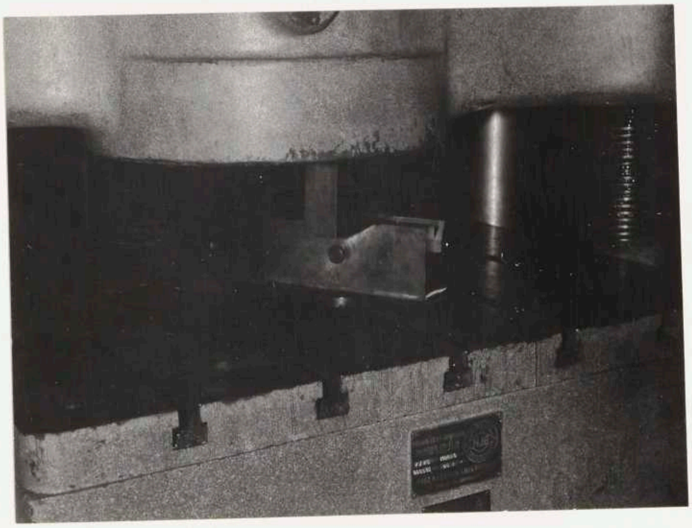

Fig. 4 - View Showing Cold-Pressing of V-Notch

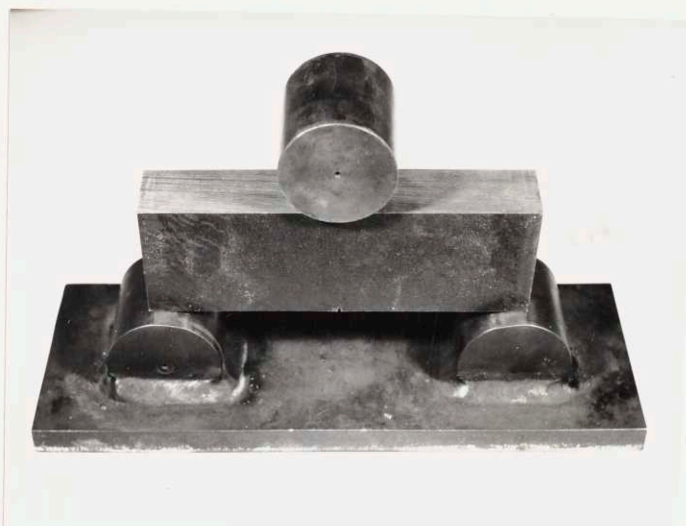

Fig. 5 - Close-up View of Loading Arrangement

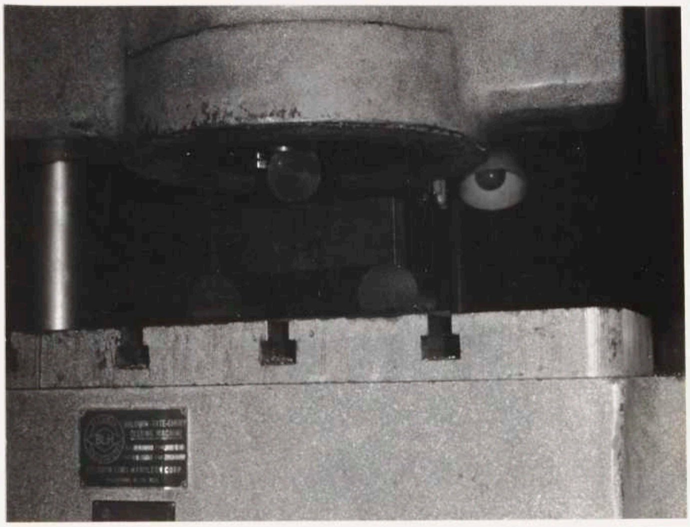

Fig. 6 - Loading in Action

Fig. 7 - Bottom View of Loading Plate with Fixing Bolt

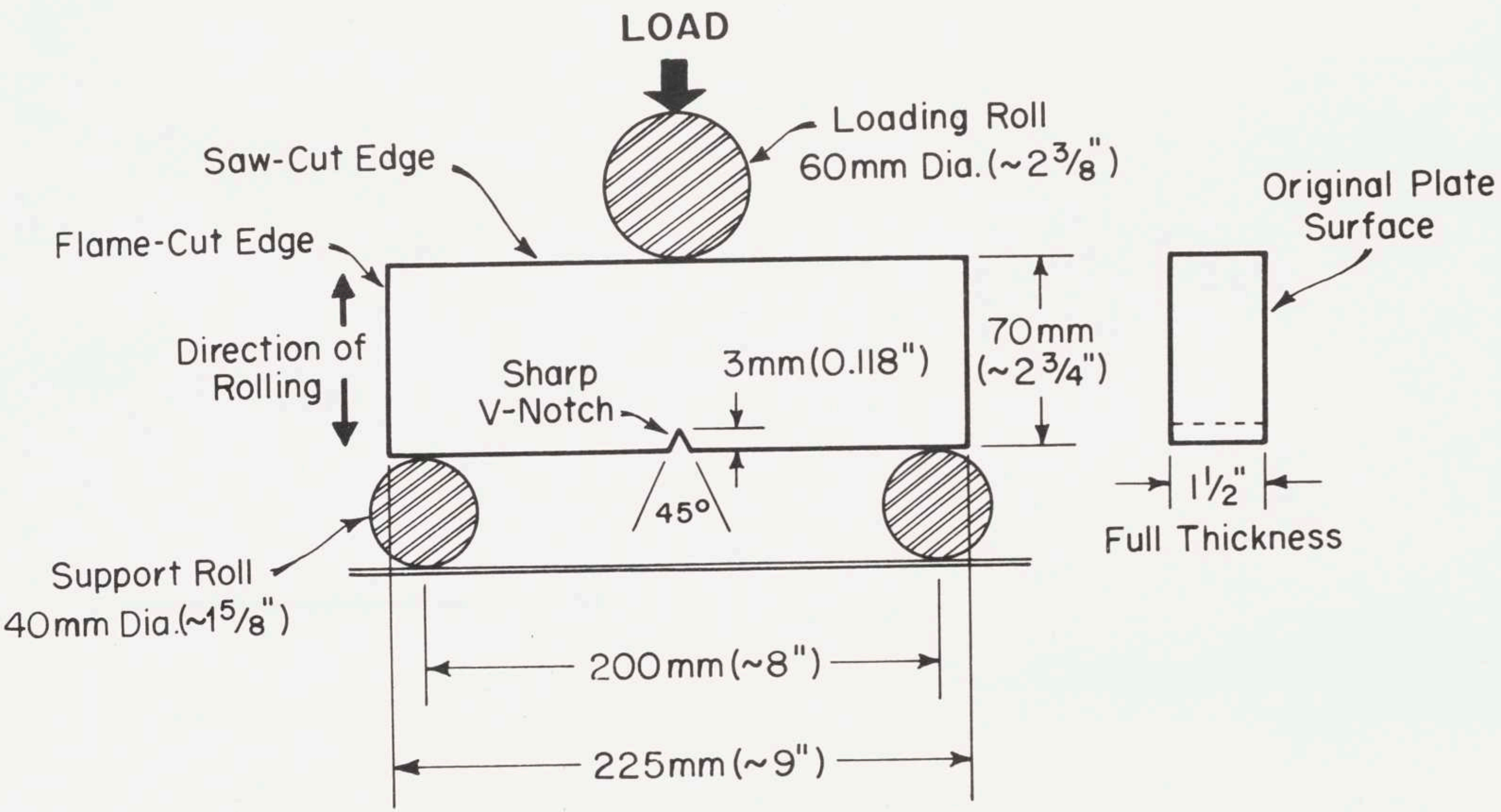

Fig. 8 - Dimensioned Drawing of the Specimen in Loading Position.

During bending a load-deflection diagram is recorded autographically from which the criteria (2) and (3), explained earlier, are determined. The specimens were tested at temperatures from about -50°C to 70°C. For below-freezing temperatures a cooling mixture of acetone and dry ice was used and water was used for higher temperatures. The specimens were immersed for at least half an hour in a bath maintained at the required temperatures, corrected by 1°C or 2°C to account for heat exchange during testing. They were tested immediately on removal from the bath and a test took from a half to one minute.

At least 20 tests were made for each sample, with three to four tests per temperature for two to three temperatures close to the transition temperature. The transition temperatures thus determined are to an accuracy of about ± 3 to ± 5°C.

2.5 Grain Size Evaluation

The ferrite grain sizes have been determined by lineal analysis on a Hurlbut grain counter. This consists of a mechanically driven stage on which the specimen is levelled and observed through a microscope at an appropriate magnification (X150). The specimen is driven alternately by two counters depending on whether the cross-hairs are in sight of the ferrite region or the pearlite region, and the individual grains of either are counted separately by two other hand-operated counters. The constant of the counter used is 2350 = 1 m.m. transverse and usually a count traverses about 100 to 150 ferrite grains.

Measurements were made in rolling, thickness and transverse directions, and, on an average, three readings were taken in obtaining any one measurement. The mean of the three values of mean ferrite path at any one position was taken as $\alpha = (\alpha_R \alpha_T \alpha_Z)^{1/3}$. This procedure was repeated, in each case, for three separate positions equally spaced over half the length of the heat-treated plate, and the reported $\bar{\alpha}$ was taken as the average of these values. The maximum variation of an averaged measurement at any position from the $\bar{\alpha}$ value was less than 7 percent and showed no definite trends. Banding ratio, defined as the ratio of the free ferrite path in the rolling direction to that in the thickness direction, was also determined.

The ASTM ferrite grain sizes have been calculated from the mean ferrite path by a method due to Rutherford et al.[17] Assuming the ferrite grains to be Kelvin equi-edged tetrakaidekahedrons which completely fill space, the number of ferrite grains per unit volume of ferrite, N_v, are:

$$N_v = \frac{0.4263}{\bar{\alpha}3}$$

$\text{Log}_{10} N_v$ is then converted to ASTM number from a tabulation given by Rutherford et al.

III. EXPERIMENTAL RESULTS AND DISCUSSION

The main readings noted during the experiment were temperature, maximum load (Lm), cleavage load (Lc) and "mm fibrous". Recorder diagrams furnished values of approximate yield load (Ly) and deflection under maximum load (Dm). Figure (9) shows a representative set of results plotted graphically for the BS material (normalized and standard-rolled), and the determination of transition-temperatures by the three criteria.

The values of transition temperatures have been tabulated below with their respective grain sizes:

TABLE II

TRANSITION TEMPERATURES AND GRAIN SIZES OF DIFFERENTLY HEAT TREATED MATERIALS

Plate	Ferrite grain size ASTM number	Transition Temperatures (°C) ± 5°C		
		"32 mm Fibrous"	$\frac{Lc}{Lm} = 0.7$	Mean maximum Deflection (Dm)
AS	7.25	27	30	13
AC	8.40	-20	-21	-40
BS	8.60	- 5	- 4	-24
BC	8.80	-18	-17	-40
CS	6.15	41	44	9
CC	6.25	28	28	13
DS*	5.80	49	52	24
DC*	5.75	40	41	21
ES	4.65	60	61	35
EC	4.65	47	48	42

* The Widmanstätten structure areas were not considered for lineal analysis.

The results of lineal analysis have been tabulated in Table VI, Appendix III and the ASTM grain size number derivation is shown in Table VII. The grains in the as-received material are slightly elongated and with progressive annealing they tend to become equiaxed. The dR/dZ and dT/dZ ratios for different heat-treatments have been tabulated in Table III.

TABLE III

GRAIN SHAPE ANISOTROPY IN DIFFERENTLY TREATED STEELS

Ratio	AS	AC	BS	BC	CS	CC	DS	DC	ES	EC
dR/dZ	1.2	1.15	1.06	1.07	1.16	1.12	0.97	0.95	1.0	1.14
dT/dZ	1.12	1.06	1.00	1.00	1.16	1.17	1.11	0.95	1.0	1.13

Figures 10, 11, and 12 show the plot of the transition temperatures, based on criteria 1, 2, and 3 respectively, against ASTM grain size numbers.

Results of fracture-appearance criteria (1) and (2) are almost coincident, the corresponding transition temperatures of the two lying within 3°C of each other. Increasing the grain size elevates the transition temperature, as expected. For both materials, between 8.5 and 6.5 ASTM grain size number, the grain size dependence of transition is linear and is about 20°C/ASTM number. Thereafter up to 4.5 ASTM grain size number the gradient diminishes gradually to about half this value. For the range of grain sizes considered, the controlled-rolled plate shows a consistent improvemtnt in notch-toughness over the conventional plate of

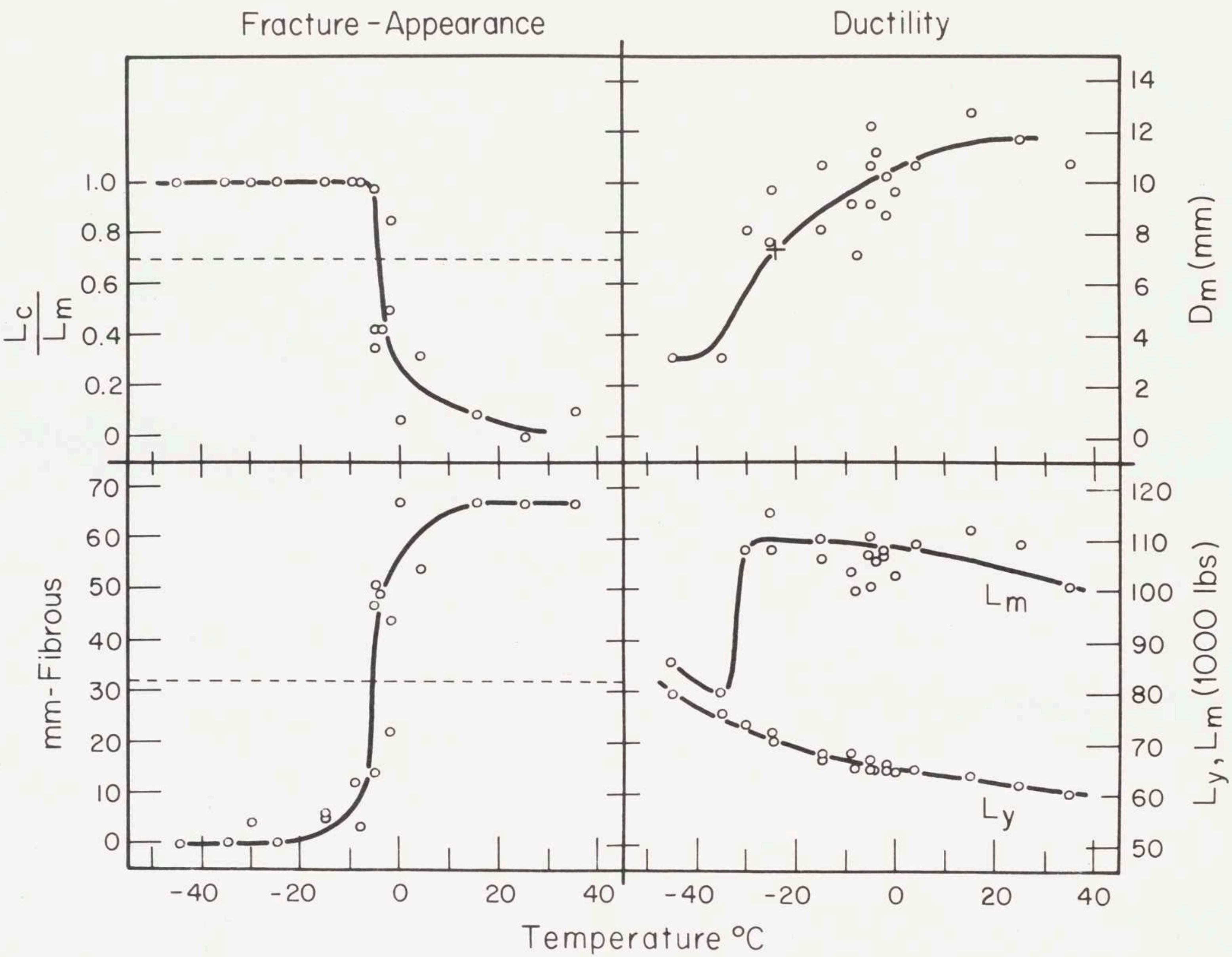

Fig. 9 - Determination of van der Veen Notched Slow-Bend Test Transition Temperatures using the Three Criteria; Temperature Dependence of Yield and Maximum Loads. (Material BS)

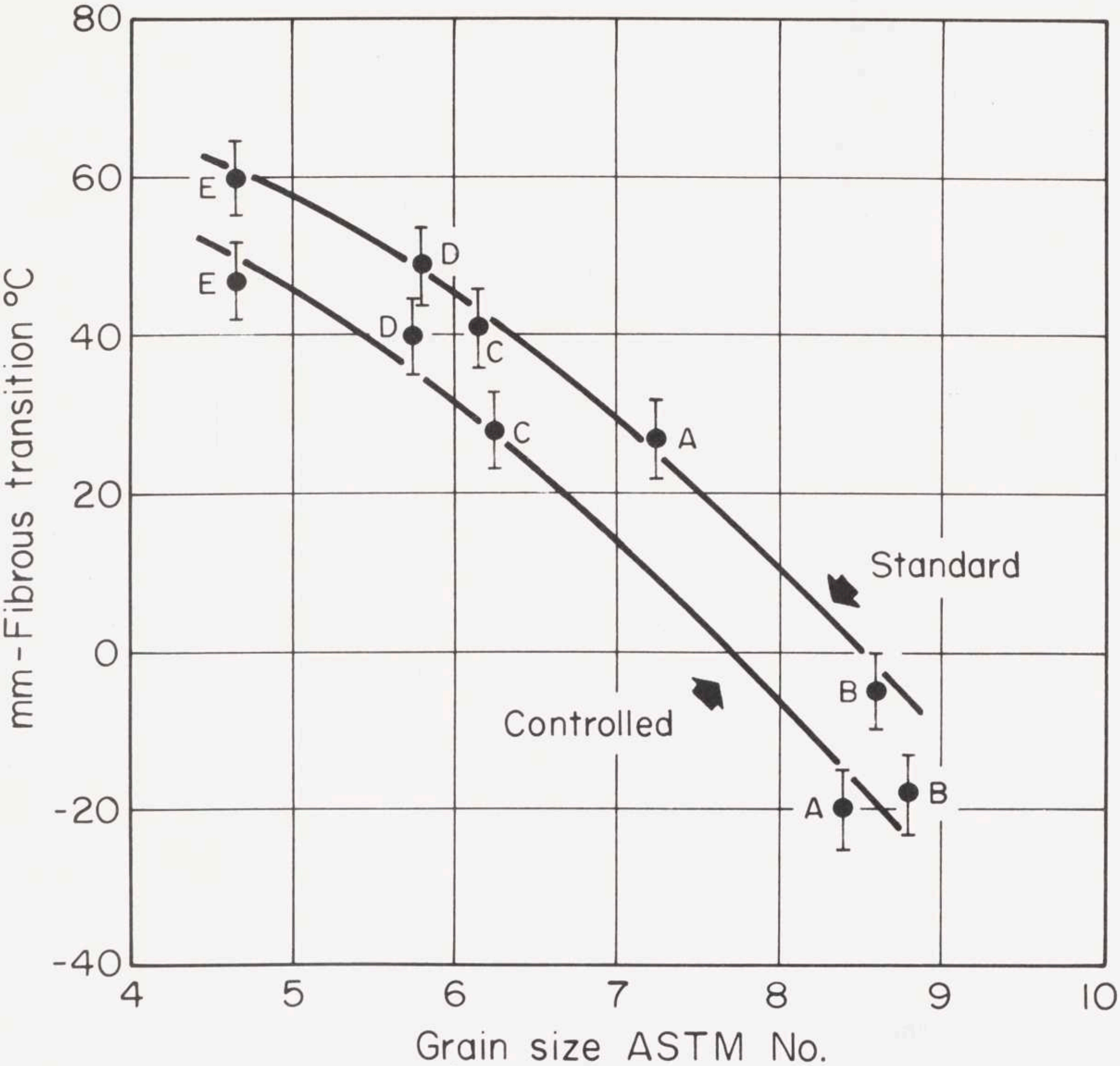

Fig. 10 - Grain Size Dependence of van der Veen Transition Temperature Based on Criterion (1)--"32 mm-Fibrous". Letters Indicate Treatments listed in Table I.

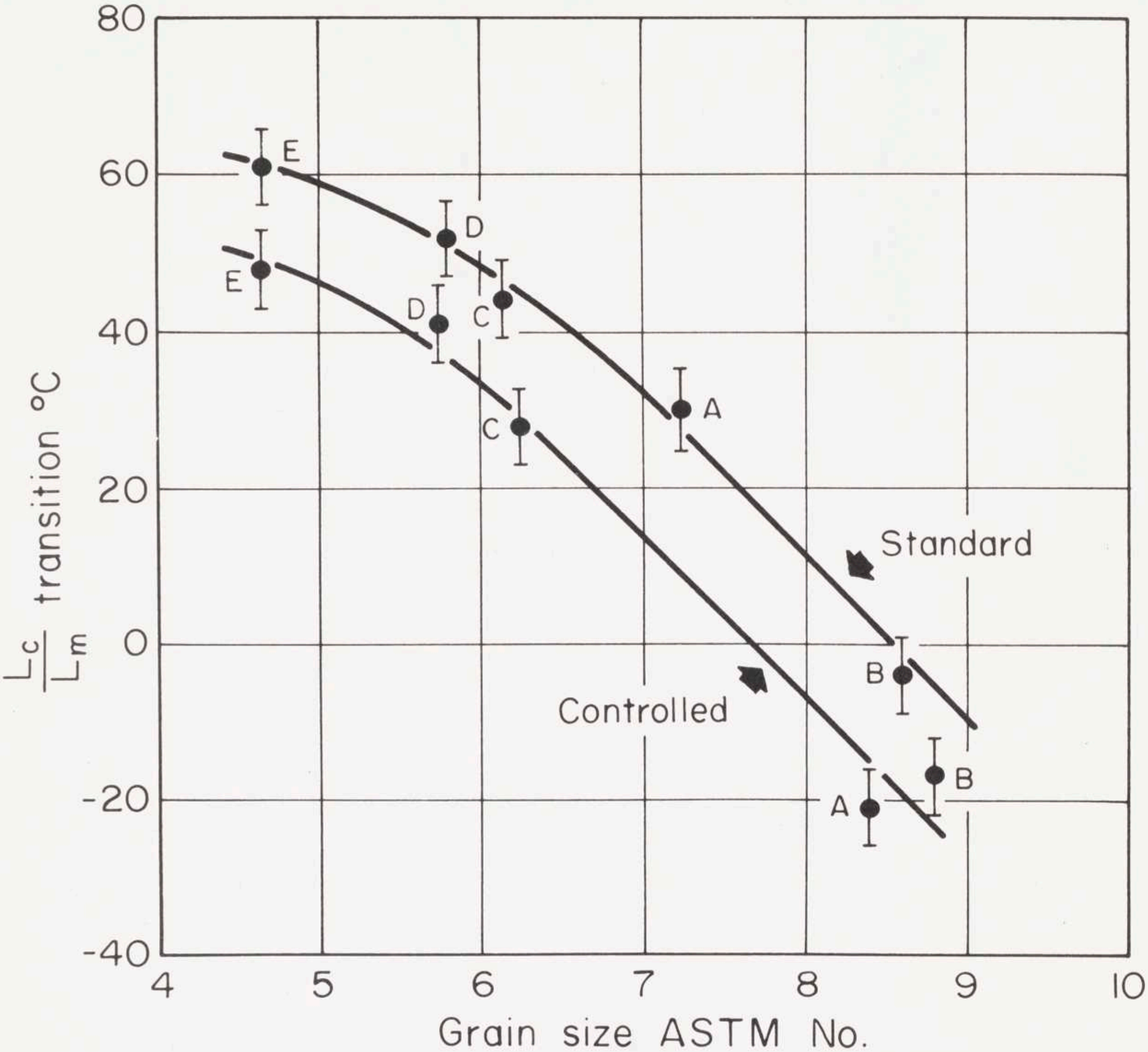

Fig. 11 - Grain Size Dependence of van der Veen Transition Temperature Based on Criterion (2)--Cleavage load/ max load = 0.7. Letters Indicate Treatments listed in Table I.

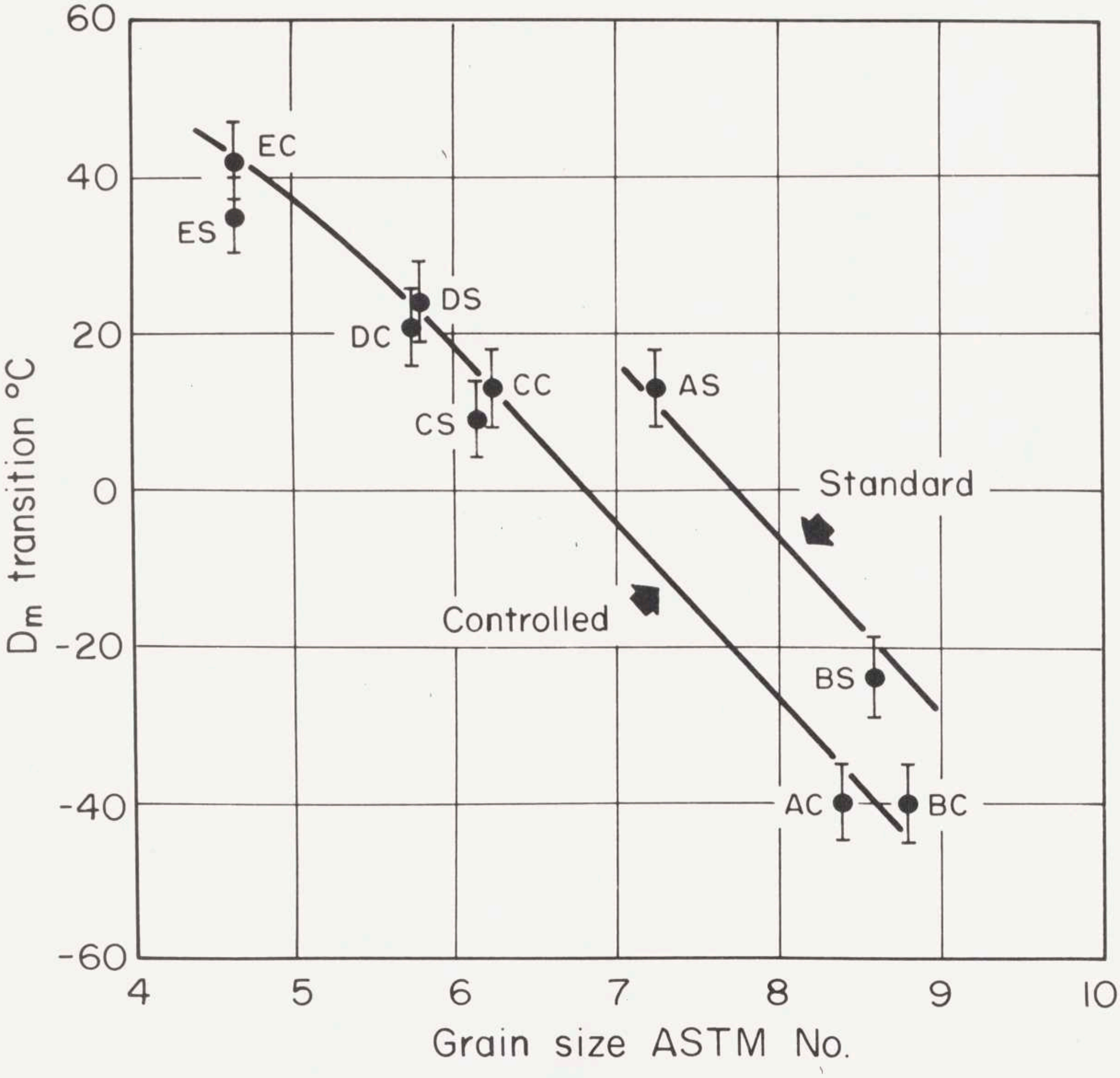

Fig. 12 - Grain Size Dependence of van der Veen Transition Temperature Based on Criterion (3)--Average Dm. Letters Indicate Treatments listed in Table I.

the same grain size; the extra-grain-size effect is about 15°C in terms of the fracture-appearance transition.

Charpy-V 15 ft.-lbs. transition results of de Kazinczy et al,[2] showed a dependence of 10°C/ASTM grain size number for the S plates and a higher value for the C plates. The extra-grain-size effect of about 6°C at 8.0 ASTM grain size number gradually vanished at coarser grain sizes.

The amount of grain size dependence of the van der Veen transition is about twice that of Charpy V-notch transition, and the former is therefore shown to be a more effective test for differentiation. The above two sets of results differ, however, in two respects: firstly that van der Veen values are based on fracture-appearance while Charpy values are based on ductility; secondly the fracture propagation is in a direction parallel to rolling in former case and perpendicular to rolling in latter case.

Increased mechanical fibering in the controlled-rolled plates provides an important reason for its superior notch-toughness for reasons explained earlier. Moreover, in the course of initiation of cleavage fracture from a progressing fibrous crack there is a zone of plastic deformation preceding the fibrous crack. The cleavage fracture therefore initiates in a material which has been plastically deformed. Due to incoherency of plastic strains in the inclusion particles and the matrix, voids appear around these particles and serve to increase the tendency to fissure. This consideration is more important in a slow-bend test than in an impact test because the fibrous crack propagates slowly and allows sufficient time for the voids to develop.

The effect of annealing has been demonstrated to spheroidize the inclusions.[2] Since the extra-grain-size effect is fairly independent of the amount of annealing it is evident that the distribution of the inclusions, and not the shape, is an important feature in providing the fine-scale flaw structure.

The ductility criteria results are inconclusive. The number of tests in the lower temperature region were insufficient for defining the minimum value of Dm and the transition temperatures determined could be expected to be slightly lower. This is evident from Dm plot in Fig. (9). However, it appears that the criterion is not a reliable one for differentiation purposes.

It is interesting to note that the presence of Widmanstätten structure (DC and DS) did not materially affect the transition temperatures and this indicates that the structural variables, other than grain size, have only a second order effect on the brittle fracture transition.

IV. CONCLUSIONS

1. In annealed structures, the ferrite grain size is the major microstructural parameter determining the transition temperature. The effects of pearlite parameters are of a secondary order.

2. The extra-grain-size improvement in transition of the controlled-rolled plates of about 15°C is fairly independent of grain size and seems unrelated to the grain size dependence of the transition temperature.

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APPENDIX I

Rolling Schedule

Ingots were 80-3/4 in. in height, measuring 31-1/4 x 60-1/4 in. at the bottom and 29-1/2 x 59 in. at the top. Reduction consisted of rolling first to slabs: 98 x 55 x 9 in. for L and H plate, and 61 x 55 x 9 in. for l and h plate. With further rolling in a two-high mill, L and H slabs were reduced to 3-1/2 in. and 4-1/4 in., respectively, and l and h were reduced to 3 in. and 2-3/4 in., respectively. The S plates were finished in a four-high mill according to more conventional practice, the temperature of the finishing pass being between 930°C and 970°C. The controlled-rolled C plates were finished with the following schedule.

TABLE IV

CONTROLLED-ROLLING SCHEDULE

Pass No.	1	2	3	4	5	6	7	8	
Pass Temp.	>910°	890°	860°	830°	800°	770°	740°	720°	After finishing pass cooling rate to 200°C
Plate	thickness, in.								
HC 1-1/2 in.	>2.25	2.08	1.93	1.80	1.67	1.56	1.46	1.46	16°C/min.
LC 1-1/2 in.	>2.25	2.13	1.97	1.81	1.69	1.56	1.47	1.47	14°C/min.
hC 3/4 in.	>1.20	1.10	1.02	0.93	0.85	0.77	0.72	0.72	16°C/min.
lC 3/4 in.	>1.18	1.08	0.99	0.90	0.83	0.75	0.70	0.70	18°C/min.

APPENDIX II

TABLE V

TRIAL HEAT-TREATMENTS

	Treatments			Grain Size ASTM No.		
No.	Temp.(°F)	time(hrs.)	Cooling Conditions			Remarks
			as received (A)	8.40	7.25	
1	1650	1.5	Furnace cooling in normal atmosphere	7.4		
		3	"	7.0		
		6	"	6.45		
		16	"	6.20		
2	1920	6	"	6.00	5.50	banded
		10	"	5.85	5.35	unbanded
		16	"	5.55	5.27	unbanded
3	2010	16	"	5.35	5.35	unbanded
		24	"	5.30	5.20	unbanded
4	2100	6	"	5.60	5.10	unbanded
		6	Furnace cooled till 1100°F in 2 hrs. and subsequently air-cooled	5.10	5.10	Appreciable Widmanstätten in S
		6	Furnace-cooled to 1450°F in 1-3/4 hrs. and then at 1.8°F/min. to 1200°F	4.45	4.70	well equiaxed grains and no Widmanstätten
		6	-do-with cooling rate 3°F/min.	5.0	--	Appreciable Widmanstätten in S

The above heat-treatments were made on 1-1/2 in. cubes of as-received material and a 1/2 in. cube was taken from the core for determining the grain size.

APPENDIX III

TABLE VI

RESULTS OF LINEAL ANALYSIS

Plate	Position	Mean Ferrite Grain Path (mm) Rolling	Thickness	Transverse	α (mm) $= (\alpha_r \alpha_t \alpha_z)^{1/3}$	$\bar{\alpha}$	Banding Ratio	Remarks
AS	1	0.0245	0.0229	0.0255	0.0242		1.14	very slightly banded
	2	0.0268	0.0214	0.0231	0.0236		1.25	
	3	0.0278	0.0214	0.0253	0.0247	0.0241	1.23	
AC	1	0.0166	0.0139	0.0146	0.015		2.33	banded structure
	2	0.0179	0.016	0.0173	0.017		1.84	
	3	0.0179	0.0158	0.0165	0.0167	0.0162	1.08	
BS	1	0.015	0.0146	0.0148	0.0148		1.20	banded structure
	2	0.0154	0.0147	0.0142	0.0148		1.16	
	3	0.0163	0.0148	0.0152	0.0152	0.015	1.28	
BC	1	0.0147	0.0132	0.0139	0.0139		1.33	banded structure
	2	0.0158	0.0149	0.0139	0.0148		1.07	
	3	0.0140	0.0135	0.0138	0.0138	0.0142	1.21	
CS	1	0.0381	0.0336	0.0414	0.0375		2.4	strongly banded
	2	0.039	0.0302	0.0355	0.0347		2.35	with distinct
	3	0.0343	0.0320	0.0346	0.0336	0.0353	1.82	pearlite bands

TABLE VI (Continued)

Plate	Position	Mean Ferrite Grain Path (mm)			α (mm)	$\bar{\alpha}$	Banding	Remarks
		Rolling	Thickness	Transverse	$= (\alpha_r \alpha_t \alpha_Z)^{1/3}$		Ratio	
CC	1	0.0353	0.030	0.0353	0.0334		2.10	strongly banded
	2	0.0330	0.0336	0.0374	0.0346		1.93	
	3	0.0367	0.030	0.0369	0.0343	0.0341	1.90	
DS	1	0.036	0.034	0.034	0.035		1.2	Widmanstatten
	2	0.037	0.041	0.045	0.041		0.91	structure in 40%
	3	0.0367	0.0383	0.047	0.041	0.039	1.2	area
DC	1	0.04	0.04	0.036	0.0386		1.08	Widmanstatten
	2	0.0395	0.043	0.043	0.0418		1.05	structure in 10%
	3	0.04	0.042	0.041	0.041	0.041	0.92	area
DS	1	0.055	0.052	0.0577	0.055		1.1	equi-axed
	2	0.07	0.062	0.064	0.065		1.65	structure
	3	0.056	0.065	0.056	0.059	0.060	0.92	
EC	1	0.064	0.059	0.070	0.064		1.15	equi-axed
	2	0.060	0.054	0.056	0.057		1.45	structure
	3	0.062	0.051	0.059	0.057	0.060	1.25	

TABLE VII

ASTM GRAIN SIZE NUMBER DERIVATION

Plate	$\bar{\alpha}$	N_v	$Log_{10}\ N_v$	ASTM No.
AS	0.024	30,500	4.48	7.25
AC	0.0162	100,000	5.0	8.4
BS	0.015	126,400	5.102	8.6
BC	0.014	149,400	5.174	8.8
CS	0.035	10,000	4.00	6.15
CC	0.034	10,800	4.033	6.25
DS	0.039	7,160	3.855	5.8
DC	0.041	6,660	3.824	5.75

SUGGESTIONS FOR FUTURE WORK

1. Results of van der Veen transition with fracture plane perpendicular to rolling direction and of Charpy with fracture plane parallel to rolling direction are important for establishing the dependence of the extra-grain-size effect on grain size.

2. Electron-microscopic technique may be applied to probe into the reasons for this extra-grain-size effect.