SSC-138

THE INFLUENCE OF MECHANICAL FIBERING ON BRITTLE FRACTURE IN HOT-ROLLED STEEL PLATE

by

B. M. Kapadia,

A. T. English,

and

W. A. Backofen

SHIP STRUCTURE COMMITTEE

SHIP STRUCTURE COMMITTEE

MEMBER AGENCIES:

BUREAU OF SHIPS, DEPT. OF NAVY
MILITARY SEA TRANSPORTATION SERVICE, DEPT. OF NAVY
UNITED STATES COAST GUARD, TREASURY DEPT.
MARITIME ADMINISTRATION, DEPT. OF COMMERCE
AMERICAN BUREAU OF SHIPPING

ADDRESS CORRESPONDENCE TO:

SECRETARY
SHIP STRUCTURE COMMITTEE
U. S. COAST GUARD HEADQUARTERS
WASHINGTON 25, D. C.

December 1, 1961

Dear Sir:

Herewith is a copy of SSC-138 entitled The Influence of Mechanical Fibering on Brittle Fracture in Hot-Rolled Steel Plate by B. M. Kapadia, A. T. English, and W. A. Backofen. This is the second progress report of a project sponsored by the Ship Structure Committee at the Massachusetts Institute of Technology to determine the relationship of mill-rolling practice to metallurgical structure and properties of ship plate.

The work has been conducted under the advisory guidance of the Committee on Ship Steel of the National Academy of Sciences-National Research Council.

This report is being distributed to individuals and groups associated with and interested in the work of the Ship Structure Committee. Please submit any comment that you may have to the Secretary, Ship Structure Committee.

Sincerely yours,

J. A. Alger, Jr.
Rear Admiral, U. S. Coast Guard
Chairman, Ship Structure Committee

Serial No. SSC-138

Second Progress Report
of
Project SR-147

to the

SHIP STRUCTURE COMMITTEE

on

THE INFLUENCE OF MECHANICAL FIBERING ON BRITTLE FRACTURE IN HOT-ROLLED STEEL PLATE

by

B. M. Kapadia A. T. English, and W. A. Backofen

Massachusetts Institute of Technology
Cambridge, Massachusetts

under

Department of the Navy
Bureau of Ships Contract NObs-72386
BuShips Index No. NS-011-078

transmitted through

Committee on Ship Steel
Division of Engineering and Industrial Research
National Academy of Sciences-National Research Council

under

Department of the Navy
Bureau of Ships Contract NObs-84321
Index No. S-R 009 03 01, Task 2004

Washington, D. C.
National Academy of Sciences-National Research Council
December 1, 1961

ABSTRACT

Further comparisons have been made between steel plates processed by conventional and controlled-rolling practices. A lower fracture-appearance transition temperature (van der Veen notched slow-bend test) of the latter material, finished at the lower temperature, could be attributed in part to smaller ferrite grain size, the grain-size dependence being 10-20 C/ASTM No. and increasing with ASTM No. Comparison of transition temperatures at constant grain size revealed additional lowering from an extra-grain-size effect which has been related to a more intensely developed fibrous structure of extra phases, weak interfaces, etc., introduced by the prior rolling. It has been argued that plastic strain accompanied by stress normal to the plane in which the fiber is aligned leads to fine-scale pore formation or microfissuring that has the result of lowering transition temperature principally because of local relaxation of stress triaxiality. The magnitude of the effect was dependent upon test method (van der Veen, Charpy, tension) in a way consistent with this view. In experiments on V-notch Charpy specimens, an internal fissuring was associated with the metallographically obvious inclusion structure after plastic strain of about 5 per cent, which occurs in all but the most brittle specimens. Findings were qualitatively consistent with transition-temperature formulas reported by van der Veen from a statistical treatment of measurements on as-rolled plate.

CONTENTS

SR-147 PROJECT ADVISORY COMMITTEE

"Mill Rolling Practice"

for the

COMMITTEE ON SHIP STEEL

Chairman:

T. S. Washburn
Manager, Quality Control Department
Inland Steel Company

Members:

J. L. Giove
Chief Metallurgist
U. S. Steel Corporation

J. R. LeCron
Bethlehem Steel Company

T. T. Watson
Manager, Metallurgical Division
Lukens Steel Company

Cyril Wells
Metals Research Laboratory
Carnegie Institute of Technology

Liaison Representative:

G. A. Pleam
Bureau of Ships
Department of the Navy

INTRODUCTION

In deformation processing, the control of properties is a problem in structure control, with the latter being influenced by modification of practice. An example underlying the present work is "controlled rolling" of steel plate. Notch toughness is improved relative to that of more conventionally rolled plate by following a reduction program in which temperature falls until the finishing pass at approximately 732 C (1350 F).[1,2] Important structural differences involve grain size and texture, or fiber, of mechanical (noncrystallographic) origin.[3] A lowering of transition temperature from refinement of ferrite grain size is well known.[4-7] Mechanical fibering as a factor in improved notch toughness has been considered in the past,[8-10] but its importance is not nearly as well established; being central to what follows, the argument for a fibering contribution is illustrated schematically in Fig. 1.

A patch of weak interface, generally associated with an included particle, is in the rolling plane. Fracture stress is lowest in the thickness (Z) di-

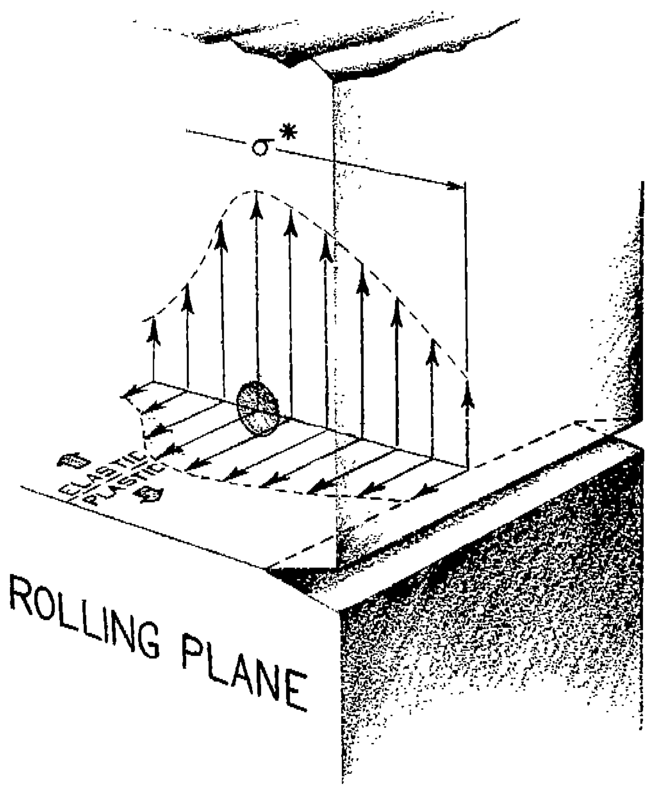

Fig. 1. SCHEMATIC REPRESENTATION OF STRESSES AT THE NOTCH IN A TENSION-LOADED PLATE, SHOWING A CRITICAL NORMAL STRESS, σ^*, FOR BRITTLE FRACTURE. IN THE FISSURING ARGUMENT, σ_Z AT THE ELASTIC-PLASTIC BOUNDARY CAUSES SEPARATION OVER THE INDICATED "WEAK PATCH," TO REDUCE STRESS TRIAXIALITY, LOWER σ_R, AND DEPRESS TRANSITION TEMPERATURE.

rection owing to the fibrous structure of such patches, and a crack runs along either the rolling (R) or transverse (T) direction, cutting the fiber as shown. Hydrostatic stress caused by the notch in a tension-loaded plate is maximum at the elastic-plastic boundary and leads to peak values of tensile stress there. A critical normal-stress criterion might be assumed to govern brittle fracture.[11] Then, if separation or fissuring occurs under σ_Z before $\sigma_R = \sigma^*$, the hydrostatic stress is eliminated locally, σ_R falls and to elevate σ_R to the σ^* level now, it is necessary to lower the test temperature; the effect is lower transition temperature. On this basis, the stress, σ_Z, to produce fissuring ought to be low relative to σ^*, e.g., $\leq 0.5\sigma^*$ according to one suggestion.[3]

Scale is an important detail in this argument, although not always emphasized sufficiently. Small volumes are involved, and it seems necessary, if the general idea is to apply, that there be small discontinuities finely dispersed in a pattern giving fissure sites within the high-stress region at the head of a crack. A difficulty in developing the argument, however, is identification of the significant structural elements. Good evidence for an appropriately fine-scale structure exists, but is mainly indirect.[12,13] In lieu of more direct information, the metallographically obvious inclusion structure has been regarded as indicating patterns in structure (shape, distribution, etc.) on an even finer scale. It is in this limited sense that the identification of "fiber" with the coarser and more routinely observed inclusions is understood, in support of such a view, some recent work has shown that transition temperature is lower, other factors being the same, as the inclusion count becomes larger (the count being made of inclusions longer than 0.02 mm).[14] The contribution of small structural discontinuities to improved notch toughness has also been demonstrated by dispersing a few per cent of alumina spheres (diameter in the micron range) in polycrystalline AgCl;[15] transition temperature of the "alloyed" sample was appreciably lower than that of the pure material, as judged by a nil-ductility (low energy) criterion in a notch impact test.

In earlier work, steel plates rolled according to controlled (C) and standard (S) practices were compared on the basis of microstructure, tensile behavior from yielding to fracture, and Charpy V-notch transition temperature; grain size, inclusion structure, test temperature, and testing direction were the variables of interest.[3] It was concluded that both smaller ferrite grain size and a greater fracturing anisotropy (associated with more fibrous inclusion structure) were responsible for the lower Charpy V-15 transition temperature of the as-rolled C stock; of a total 15 C difference between the as-rolled materials, 10 C was attributed to the grain-size effect and the balance to the extra-grain-size effect of microscale fissuring (microfissuring).

With this background, there were two objectives in further study one additional metallographic evidence of the fissuring process, the other related to the differences in toughness evaluation that follow the use of different test criteria. In particular, it was of interest to establish effects of both grain size and microfissuring in the notched slow-bend test of van der Veen.[16] The test appears well suited to assessing the tendency for conversion of a ductile tear into a brittle, fast-moving cleavage crack, and it has long been associated with the development of controlled rolling: rather striking differences between controlled and conventionally processed plates have, in fact, been illustrated by its use.[16]

MATERIALS

A single composition and plate thickness of 1-1/2 in. were selected. The basic analysis was .15% carbon with a Mn/C ratio of about 8. Rolling was done by the Royal Netherlands Blast Furnace and Steel Works, Ltd. Chemistry and processing history have been described in detail.[3] Two rolling practices were followed. controlled, with finishing at approximately 732 C (1350 F), designated C, and standard, with finishing at 954 C (1750 F), designated S. Ferrite grain size in the as-rolled condition was ASTM No. 8.5 for C and ASTM No. 7.5 for S. Other ferrite grain sizes as large as ASTM No. 4 were obtained in both C and S stock, by different annealing heat-treatments in the austenitic range (Table I) to establish the grain-size dependence of

TABLE I

HEAT-TREATMENT DATA FOR TEST MATERIAL TO OBTAIN DIFFERENT GRAIN SIZES REPRESENTED IN FIG. 5

Code in Fig. 5	Heat Treatment	ASTM NO.	
		C	S
A	as-rolled	8.4	7.25
B	1650 F, 1/2 hour; air cool	8.8	8.6
C	1700 F, 6 hours; retort cool*	6.25	6.15
D	2100 F, 6 hours; retort cool*	5.75	5.8
E	2100 F, 7 hours; furnace cool	4.65	4.65
F	1700 F, 1-1/2 hours, retort cool*	7.44	(+)

*Cooling rate intermediate between that of air cooling and furnace cooling.
+Not tested.

transition temperature. (Detailed data and results are presented in the Appendix). In this way, the effects of processing differences could be related to other structural details, in particular the fibering, by making comparisons of transition temperature at fixed grain size.

FISSURING OBSERVATIONS

Direct observation of fissuring was attempted in conventional Charpy V-notch specimens* tested in the transition-temperature range. Some of the specimens were broken, while others were only bent by blows of various low energies; the correlation between energy absorbed and bend angle, from -40 C (-40 F) to

*Specimens in rolling direction; notch in thickness direction.

room temperature for all specimens, whether broken or not, is given in Fig. 2. Metallographic sections were prepared on a T-Z plane through the notch root (defined by the thickness and transverse directions), with the results shown in Fig. 3. A porosity or fissuring caused by separation at inclusion-ferrite interfaces was evident in all but the brittlest specimens. It is demonstrated quite clearly in Fig. 3 that increasing amounts of energy absorbed are accompanied by an increasingly large porous region, the depth of which can also be related to specimen deformation by means of Fig. 2. These findings leave little doubt that separation around inclusions is associated with plastic flow.

To estimate the strains involved in producing the first visible fissures, microhardness measurements were made in the ferrite regions, starting at the notch root and moving in a direction towards the interior of the specimen (left to right in Fig. 3). Hardness was relatively high adjacent to the notch, decreasing with distance inwards to a base value for undeformed metal of DPH 119. By comparing the microhardness plots with Fig. 3, the maximum distance to which porosity penetrated beneath the notch was identified with a hardness of roughly DPH 135. Turning then to a hardness: shear-strain correlation from torsion testing of this same material, the "critical" strain for fissure formation was found to be 10% in shear, or a normal strain of about 5%.

A strain of 5% at the notch root in a Charpy bar has been related to a bend angle of about 0.5°,[17] or, from Fig. 2, around 6 ft-lb absorbed. By way of check, fissuring could be observed in Charpy specimens absorbing as little as 6 ft-lb, but not less. In addition, fissuring in the torsion specimens (in which strain increases linearly with distance from the center) occurred only beyond a well-defined radius at which the shear strain was 10%. Thus, a rather small strain, present in all but the most brittle Charpy specimens (or well below the usual ductility-transition temperature), seems sufficient to ensure some local fissuring.

NOTCHED SLOW-BEND TESTS

A series of van der Veen tests was also completed on both the as-rolled

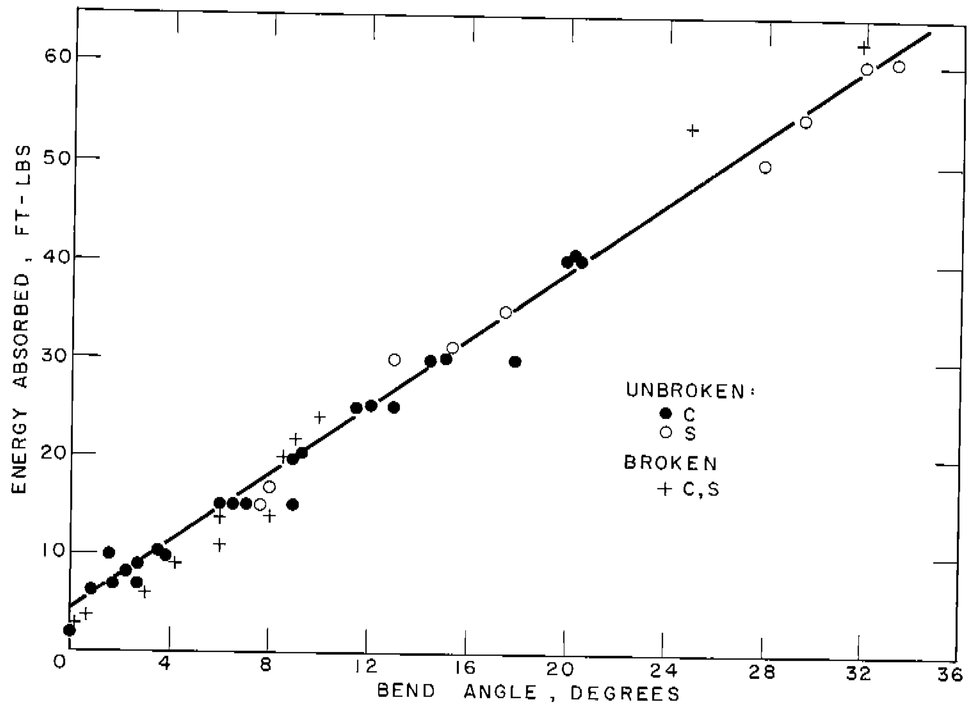

Fig. 2. ENERGY REQUIRED TO BEND PLASTICALLY A CHARPY-V SPECIMEN THROUGH VARIOUS ANGLES.

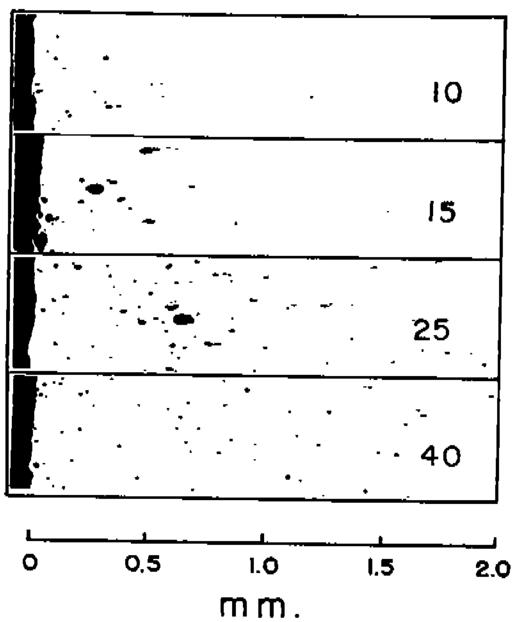

Fig. 3. T-Z PLANES THROUGH CHARPY-V SPECIMENS WHICH ABSORBED ENERGIES INDICATED AT RIGHT (FT-LB); NOTCH ROOT IS AT LEFT. ZONE OF INCLUSION-MATRIX SEPARATION IS LARGER FOR GREATER ENERGIES ABSORBED. 15X.

and heat-treated plate, for reasons noted above.

The specimen for this test is of full-plate thickness and taken along the transverse direction. The crack initiates at the root of a pressed notch and grows parallel to the fiber elements, i.e., in the rolling direction rather than cutting across the fiber as in the Charpy test. The resulting fracture surface is nearly plane and is characterized by a symmetrical fibrous "tongue" extending from the notch and varying in length with temperature (Fig. 4, left). At the fracture-appearance transition temperature commonly measured in the van der Veen test, the fibrous tongue extends 32 mm from the notch, the surface immediately beyond that point representing cleavage fracture. Twenty to twenty-five tests were made to establish the transition temperature in each plate.

Test results from plates heat treated to the different grain sizes are summarized in Fig. 5. The ASTM number representing ferrite grain size is based on a mean ferrite-grain intercept $\overline{\alpha}$ computed at various locations in a plate from the expression $\overline{\alpha} = \sqrt[3]{\alpha_R \alpha_T \alpha_Z}$, where the α values are obtained by lineal analysis along the three principal directions of the plate. The number of grains per unit volume of ferrite (N_V) can be computed from $\overline{\alpha}$,[5] which then allows determination of either the ASTM grain-size number[18] or a mean grain diameter $\overline{d}$.[19] Uncertainty in the ASTM No. was estimated to be no greater than $\pm$ 0.2 of a unit. The grain-size dependence of transition temperature is about 20C/ASTM No. for the finer grain sizes, decreasing towards 10C/ ASTM No. at ASTM 4.5. Interestingly, a linear relation is found when transition temperature is plotted against $\overline{d}^{-1/2}$. Transition temperature is clearly lower for controlled-rolled material at any grain size, the extra-grain-size effect being about 15C at ASTM 8.5, decreasing to 10C at ASTM 4.5. Whether there has been a sharp separation of structural effects in Fig. 5 may be questioned, since the annealing treatments to coarsen grain size also served to lower the fracturing anisotropy, through the grain-size enlargement in the first place, and also through spheroidization of the inclusion (fiber) structure.[3] Results cannot be changed significantly, however, although it might be argued,

Fig. 4. FRACTURE SURFACES OF SLOW-BEND TEST SPECIMENS, ILLUSTRATING FRACTURING ANISOTROPY ASSOCIATED WITH DIFFERENT CRACK PATHS. LEFT, CONVENTIONAL ORIENTATION, CRACKING PARALLEL TO THE FIBER. RIGHT, CRACKING ACROSS THE FIBER, AS IN CHARPY TESTS. AS-ROLLED C PLATE. PRESSED NOTCH AT BOTTOM. ABOUT .5X

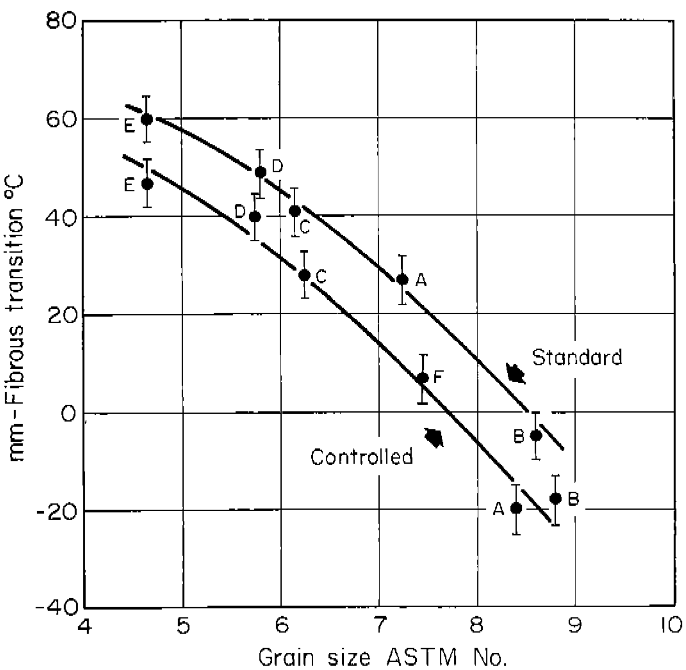

Fig. 5. TRANSITION TEMPERATURE (32-MM FIBROUS CRITERION OF VAN DER VEEN) VS. ASTM GRAIN-SIZE NO. FOR THESE EXPERIMENTS THE BOUNDS OF ± 5 C ENCOMPASSED ALL MEASUREMENTS AROUND THE 32-MM FIBROUS LEVEL.

with consideration for this possibility, that the grain-size dependence of transition temperature given by Fig. 5 is somewhat too high.

A few of the slow-bend tests were also conducted with the specimen axis taken parallel to the rolling direction (perpendicular to the orientation prescribed by van der Veen) which gives the crack path of the Charpy test. Now the fracture appearance contrasted sharply with that for the transverse orientation (Fig. 4). Extensive shear deformation on a macroscopic scale preceded fracture. A gross fissuring occurred chiefly in the fibrous zone which was ill-defined, irregular, and unsymmetrical. For as-rolled plate, the 32-mm transition temperature was lowered as much as 10 C, compared with the prescribed orientation.

DISCUSSION

The observations fit into two related categories:

1. The association of fissuring, or internal pore formation, with plastic flow.
2. The marked extra-grain-size effect, attributed to fissuring, in the van der Veen test.

With regard to the first, a simple stress condition for fissuring, as referenced in the Introduction, is generally in accord with the evidence that stress perpendicular to the fiber plane facilitates pore formation. An example from experiments related to the present work is the holes that appear around inclusions almost immediately after yielding in a tensile specimen taken through the thickness direction, so that the applied stress acts normal to the fiber from the beginning.[3] On the other hand, in tests along the rolling (or fiber) direction, porosity becomes apparent only as necking sets in and transverse stresses, normal to the fiber, are developed. Yet it is hardly enough to consider stress alone, for here both notch-bar impact and torsion led to the initiation of fissuring at approximately the same plastic strain, but under very different stress systems; there are various examples to be interpreted as showing that a plastic-strain-induced porosity is initiated from incompatibility in strain between the matrix and a particle of some secondary phase.[20] Any general criterion most probably ought to consider stress and plastic strain together; then it will likely have significance in other areas as well, as in the initiation of ductile fracture discussed in recent papers by Rogers[21] and Puttick.[22,23]

In the second category, data of Fig. 5 are distinguished both by the magnitude of the extra-grain-size effect and its persistence to large grain size. A rationale for the former can be found in the circumstance that fracture under these conditions develops out of a severely strained region in which rather extensive fissure formation is to be expected. The effect persisting to large grain size is unexpected, however, since fiber spheroidization (observed microscopically as happening to inclusions) increases as grains are coarsened. Possibly, if the distribution as well as the shape of fiber elements is considered, even rounded particles disposed in more or less flat arrays still contribute through fissure formation to an extra-grain-size effect. But whatever the detailed explanation, the impression is reinforced of unusual sensitivity of the van der Veen test to differences in fibering intensity. Still another index of sensitivity is the variation in fracture transition with direction in a plate which is due to fibering directionality; in view of this, it seems reasonable to encounter variations for a given direction between plates with different processing histories (and fibering characteristics).

The results of both past[3] and present work on these same plates fit into a pattern illustrating how the extra-grain-size effect owing to fissuring depends on test conditions. The van der Veen data are extreme in their indication of the greatest effect, for the reason suggested. The Charpy data (V-notch 15 ft-lb transition temperature) are less so; the smaller effect, by a factor of 2 to 3, is consistent, however, with a transition relating more to initiation of cleavage in an initially uncracked and undeformed specimen--and to less extensive fissuring with correspondingly less influence on transition temperature from this source. At the other extreme are measurements of ductility-transition temperature in pure tension defined by the intersection of curves relating tensile yield and fracture stresses to test temperature; no extra-grain-size effect was observed in this case. Transition in tension specimens taken along the rolling direction varied only with grain size, as might be expected in the absence of a macroscopic triaxiality for inducing fissuring

Other developments related to these findings, in the way of formulas for calculating transition temperature, have recently been reported by van der Veen.[14] The basis of this contribution was statistical treatment of test data from many plates that led to expressions of the form

$$T = A + B(\%\ C) - C(\%\ Mn) + D(\%\ P) - E(\text{ASTM No.}) - F(q).$$

Coefficients of all terms change with the criterion for measuring transition temperature; the last two terms have structural origins of interest here.

For the van der Veen fracture-transition temperature (Fig. 5), E = 16.8 C/ASTM No. is in broad agreement with the range of values found in the present work of 10-20 C/ASTM No., depending on grain size.

The quantity q is the number of inclusions longer than 0.020 mm intersecting a line of 10-cm length perpendicular to the surface of the plate and viewed in the R-Z plane. It is determined by the size and shape of individual particles as well as the amount of included material. Since more elongated inclusions from controlled rolling are reflected in greater q, it is also a measure of fiber intensity. The coefficient F is, in turn, a measure of the influence of fibering on transition temperature, the negative sign meaning that a larger inclusion count is associated with increased toughness. Its dependence on test criterion fits the pattern just discussed, the value being greater for the test in which fissuring is more important. Specifically, F is 0.28 for the van der Veen 32-mm fibrous transition, but is only 0.09 for the Charpy V-15 transition temperature

Further use of the F(q) term in discussing the extra-grain-size effect is limited, however, because the formula is not quantitatively consistent with the observed effect. A principal reason is quite likely to be found in the different thermal histories for producing the grain-size range in Fig. 5; another is the probability that the statistically derived constant "A" is structure dependent and somewhat variable from plate to plate. It was discovered that F(q) dropped markedly after the heating cycles that gave ASTM Nos. less than 6, and became essentially the same for both C and S stock. Evidently, this measure of fibering intensity may be applicable to plates in the as-rolled condition, which were the basis of the development, but not after the additional heat treatment.

Altogether, the results presented lend further support to an earlier conclusion that low-temperature finishing can lead to improved notch toughness for reasons of more intense fibering as well as grain-size refinement.[3] From work such as that of Sohlberg, reported by Lightner and Vanderbeck,[1] as well as other work in progress, it is also recognized that temperature so low as to leave cold-working effects results in increased transition temperature. Therefore, the development of structure for optimum properties involves control of at least the three details of grain size, fibering characteristics, and residual working effects.

SUMMARY

Several factors are involved in the formation of fissures on a microscale: the presence of finely dispersed fiber elements, plastic strain, and a stress normal to any plane in which the fiber is aligned. The fiber elements are identified with inclusions; the amount of plastic strain for the beginning of fissuring is relatively small, approximately 5% local elongation being sufficient in the material studied, the stress usually results from a notch and encourages the growth of the separation.

The strain and stress factors are found to different degrees in the various tests, so that the contribution of the extra-grain-size effect to transition temperature depends on the test employed and the criterion for transition. A classification is suggested from van der Veen notched slow-bend, to Charpy

V-notch, and finally to pure tensile loading, on the basis of decreasing tendency to promote fissuring at transition. Using the van der Veen test and 32-mm fibrous criterion, the transition temperature for controlled-rolled plate is lowered because of reasons other than grain refinement by 10-15 C, or 2-3 times that when the temperature is taken at the Charpy V-notch 15 ft-lb level; and this compares with no extra-grain-size effect in the ductility transition measured under pure tensile loading.

ACKNOWLEDGMENTS

This work was part of a continuing program of research sponsored by the Ship Structure Committee and under the advisory guidance of a Project Advisory Committee of the Committee on Ship Steel of the National Academy of Sciences-National Research Council.

REFERENCES

1. Lightner, W. M., and Vanderbeck, R. W., "Factors Involved in Brittle Facture," AISI Regional Technical Meetings, p. 427, 1956.

2. Vanderbeck, R. W., "Controlled Low-Temperature Hot Rolling as Practiced in Europe," The Welding Journal, 37:3, Research Supplement, pp. 114s-116s (March 1958).

3. De Kazinczy, F., and Backofen, W. A., "Influence of Hot-Rolling Conditions on Brittle Fracture in Steel Plate," Trans., ASM (ASM 1960 Preprint No. 182), Vol. 52, 1960.

4. Frazier, R. H., Boulger, F. W., and Lorig, C. H., "Influence of Heat Treatment on the Ductile-Brittle Transition Temperature of Semi-Killed Steel Plate," Trans., AIME, Vol. 203, p. 652, 1954.

5. Owen, W. S., Whitmore, D. H., Cohen, M., and Averbach, B. L., "Relation of Charpy Impact Properties to Microstructure of Three Ship Steels," The Welding Journal, 36:11, Research Supplement, pp. 503s-511s (November 1957).

6. Hodge, J. M., Manning, R. D., and Reichhold, H. M., "The Effect of Ferrite Grain Size on Notch Toughness," Journal of Metals, Vol 1, p. 233 (1949).

7. Heslop, J., and Petch, N. J., "Dislocation Locking and Fracture in α-Iron," Philosophical Magazine, Vol. 2, p. 649 (1957).

8. Soete, W., "Transverse Strength and Brittle Fracture," Journal of the West of Scotland and Iron and Steel Institute, Vol. 60, p. 276 (1952-53).

9. Matton-Sjöberg, P., "The Mechanism of Fracture in Impact Tests," Journal of the West of Scotland Iron and Steel Institute, Vol. 60, p. 180 (1952-53).

10. Mangio, C. A., and Boulger, F. W., "The Effect of Variations in Texture on Energy Absorption and Transition Temperature," An Appraisal of the Properties and Methods of Production of Laminated or Composite Ship Steel Plate (Ship Structure Committee Report Serial No. SSC-84), Washington National Academy of Sciences-National Research Council, Appendix A, January 12, 1956.

11. Hendrickson, J. A., Wood, D. S., and Clark, D. S., "The Initiation of Brittle Fracture in Mild Steel," Trans. ASM, Vol. 50, p. 656 (1958).

12. Backofen, W. A., and Hundy, B. B., "Mechanical Anisotropy in Some Ductile Metals," Journal of the Institute of Metals, Vol. 81, p. 433 (1952).

13. Backofen, W. A., Shaler, A. J., and Hundy, B. B., "Mechanical Anisotropy in Copper," Trans. ASM, Vol. 46, p. 655 (1954).

14. Van der Veen, J. H., Influence of Steel-Making Variables on Notch Toughness (Ship Structure Committee Report Serial No. SSC-128), Washington National Academy of Sciences-National Research Council, June 27, 1960.

15. Johnston, T. L., Stokes, R. J., and Li, C. H., "Fundamental Mechanical Behavior of Composite Crystalline Mixtures," Composite Materials and Composite Structures (Proceedings of the Sixth Sagamore Ordnance Materials Research Conference), August 18-21, 1951.

16. Van der Veen, J. H., "Development of a Testing-Method on Brittle Fracture of Mild Steel Plate," Notch Bar Testing and Its Relation to Welded Construction. 2 Buckingham Palace Garden, S. W. 1, London: Institute of Welding, 1953.

17. Lequear, H. A. and Lubahn, J. D., "Root Conditions in a V-notch Charpy Impact Specimen," The Welding Journal, 33-12, Research Supplement, pp. 585s-588s (December 1954).

18. Rutherford, J. B., Aborn, R. H., and Bain, H. C., "The Relation Between the Grain Areas on a Plane Section and the Grain Size of a Metal," Metals and Alloys, Vol. 8, p. 345 (1937).

19. Lement, B. S., Averbach, B. L., and Cohen, Morris, "Microstructural Changes on Tempering Iron-Carbon Alloys," Trans., ASM, Vol. 46, p. 851 (1954).

20. Backofen, W. A., "Metallurgical Aspects of Ductile Fracture," Proc., ASM (Eastern New York Chapter), Presented at Conference on Fracture of Engineering Materials, August 24-25, 1959. (To be published).

21. Rogers, H. C., "The Tensile Fracture of Ductile Metals," Trans., AIME, Vol. 218, p. 498 (1960).

22. Puttick, K. E., "Ductile Fracture in Metals," Philosophical Magazine, Vol. 4, p. 964 (1959).

23. Puttick, K. E., "The Shear Component of Ductile Fracture," Philosophical Magazine, Vol. 5, p. 759 (1960).

APPENDIX

A representative set of test data from the conventionally rolled plate (S), heat treated according to code B in Table I, is plotted in Fig. 6 to illustrate the evaluation of all van der Veen transition temperatures.[16] The fracture-appearance transition temperature is defined as the temperature at which a fibrous tongue extends 32 mm below the notch. The temperature at which the cleavage load, L_c, is 0.7 of the maximum load, L_m, may be taken as one measure of the ductility transition; the temperature at which the deflection at maximum load, D_m, is the average of its greatest and least values may be taken as another.

The grain-size dependence of all such transition temperatures is shown in Fig. 5 of the text and in Figs. 7 and 8 of this Appendix.

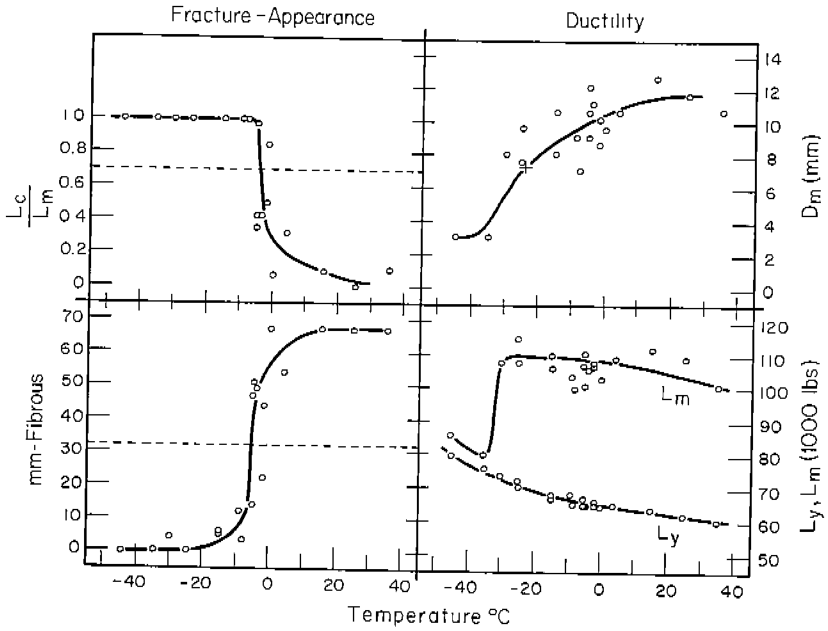

Fig. 6. REPRESENTATIVE TEST DATA FROM STANDARD ROLLED PLATE WITH HEAT TREATMENT B, SHOWING HOW THE L_c/L_m, "32 mm FIBROUS," AND D_m TRANSITION TEMPERATURES WERE DETERMINED. THE TEMPERATURE DEPENDENCE OF THE YIELD LOAD, L_y, AND MAXIMUM LOAD, L_m, ARE SHOWN AT THE LOWER RIGHT.

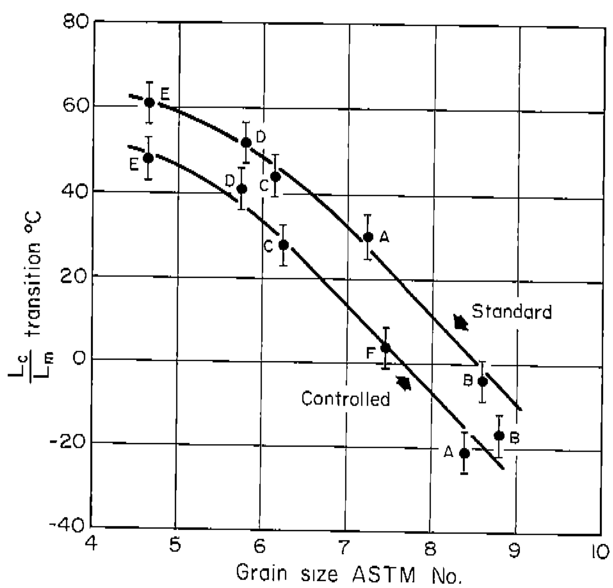

Fig. 7. GRAIN SIZE DEPENDENCE OF THE VAN DER VEEN TRANSITION TEMPERATURE BASED ON THE "CLEAVAGE LOAD/MAXIMUM LOAD = 0.7" CRITERION. AN UNCERTAINTY OF 5 C IS INDICATED AT EACH EXPERIMENTAL POINT. LETTERS INDICATE HEAT TREATMENTS LISTED IN TABLE I.

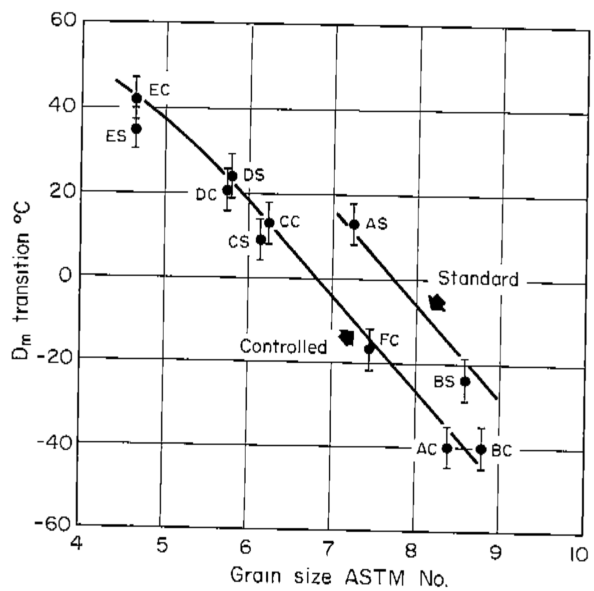

Fig. 8. GRAIN SIZE DEPENDENCE OF THE VAN DER VEEN DUCTILITY TRANSITION TEMPERATURE. AN UNCERTAINTY OF 5 C IS INDICATED AT EACH EXPERIMENTAL POINT. LETTERS INDICATE HEAT TREATMENTS LISTED IN TABLE I AND STANDARD (S) OR CONTROLLED (C) ROLLING PRACTICES.

COMMITTEE ON SHIP STEEL

Chairman

Professor John Chipman
Head, Department of Metallurgy
Massachusetts Institute of Technology

Vice Chairman

Mr. M. W. Lightner
Vice President Research and Technology Division
United States Steel Corporation

Members

Professor C. S. Barrett
Institute for the Study of Metals
University of Chicago

Professor D. K. Felbeck
Department of Mechanical Engineering
University of Michigan

Mr. Paul Ffield
Assistant Manager of Research
Bethlehem Steel Company

Professor Maxwell Gensamer
Professor of Metallurgy
School of Mines
Columbia University

Dr. J. R. Low, Jr.
Metallurgy Research Unit
Research Laboratory, General Electric Co.

Mr. T. S. Washburn
Manager, Quality Control Department
Inland Steel Company

Mr. T. T. Watson
Director of Research
Lukens Steel Company