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**THE INFLUENCE OF FERRITE BANDING
ON THE IMPACT PROPERTIES OF MILD STEEL**

by

W. S. Owen

Morris Cohen

and

B. L. Averbach

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October 6, 1958

Dear Sir:

As a part of its research effort in the field of brittle fracture the Ship Structure Committee is sponsoring a study at Massachusetts Institute of Technology of the influence of metallurgical structure on the fracture behavior of ship steel. Herewith is the Fourth Progress Report, SSC-114, of this project, entitled "The Influence of Ferrite Banding on the Impact Properties of Mild Steel" by W. S. Owen, Morris Cohen and B. L. Averbach.

This project is being 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 or interested in the work of the Ship Structure Committee. Please submit any comments that you may have to the Secretary, Ship Structure Committee.

Sincerely yours,



E. H. Thiele
Rear Admiral, U. S. Coast Guard
Chairman, Ship Structure
Committee

Serial No. SSC-114

Fourth Progress Report
of
Project SR-136

to the
SHIP STRUCTURE COMMITTEE

on

THE INFLUENCE OF FERRITE BANDING
ON THE IMPACT PROPERTIES OF MILD STEEL

by

W. S. Owen

now with

University of Liverpool, England

and

Morris Cohen and B. L. Averbach

Massachusetts Institute of Technology
Cambridge, Massachusetts

under

Department of the Navy
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Division of Engineering and Industrial Research
National Academy of Sciences-National Research Council

under

Department of the Navy
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Washington, D. C.
National Academy of Sciences-National Research Council
October 6, 1958

ABSTRACT

↙ The object of this investigation was to compare the Charpy properties of a severely banded ferrite-pearlite structure with those of a random ferrite-pearlite distribution. Both types of specimens could be prepared from the same material by applying suitable homogenizing treatments to an initially banded steel. Some observations on the nature of the banding are described.

The Charpy properties at the lower end of the testing-temperature range are not appreciably affected by the degree of ferrite banding, by the direction of the specimen axis, or by the orientation of the notch. However, in the higher temperature range, the random structure exhibits a higher energy absorption than does the banded structure and, in both cases, the Charpy values depend strongly on the orientation of both the specimen and the notch. Evidence was obtained to suggest that the fracture appearance is not sensitive to specimen orientation even in a severely banded steel, although notch orientation is a factor

No preferred crystallographic orientation of the ferrite was found in any of the specimens. ↘

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INTRODUCTION

There is good reason to suppose that the fracture properties of mild steel can be influenced by the texture of the microstructure. In discussing the condition for crack propagation

$$\sigma \sim \left(\frac{Ep}{c}\right)^{1/2}$$

(where σ is the normal stress needed for crack propagation, E is Young's modulus, c is the crack length, and p is the plastic work required for the formation of unit area of surface). Orowan¹ has suggested a number of ways in which p and consequently σ , might be increased. One of these involved laminating the plate by incorporating layers of either a weak or a highly ductile material. A weak layer, such as slag, should burst open ahead of the crack, annihilating the triaxiality, and causing some fibrous fracture to occur before the necessary triaxiality for brittle fracture can be re-established. Alternatively, an increase in p can be achieved by rolling thin layers of a tough metal into the plate. Unfortunately, it is very difficult to obtain precise values of p for different materials under the conditions envisaged here, and thus no accurate estimate of the quantitative effect is possible. If it is assumed that the values of p for ferrite and pearlite are appreciably different, ferrite banding in mild steel is a form of lamination that should influence the fracture properties. Several experimental studies have been made of the effect of ferrite-pearlite banding on the impact properties, but the results are somewhat ambiguous.

Matton-Sjöberg² compared the notch-bar properties of two similar steels with different degrees of banding and concluded that a lower transition temperature was associated with the finer banding. Tipper³ has also investi-

gated this problem on the same steels. Pellini reported in a private communication that, in numerous tests of banded steels, only the one with wide bands of severe alloy segregation showed increased resistance to brittle fracture. In contradistinction, Mangio and Boulger⁴ concluded that a banded microstructure is less resistant to brittle fracture than a uniform unbanded structure. In support of this statement, they quoted the work of Sims, Banta and Waters⁵ who compared high tensile steel plates rolled from slabs of the same ingot, one slab being given an intermediate homogenizing treatment for ten hours at 2350 F. Homogenizing the slab lowered the 10 ft-lb Charpy V-notch transition temperature of the plate by about 60 F. However, in the original report by Sims et al,⁵ it was stated that the "...microstructure of the annealed plate rolled from the homogenized slabs showed strong evidence of banding and no influence of the homogenizing treatment." Thus it seems questionable to ascribe the improvement in transition temperature to a change in the extent of banding.

In a study of the quantitative relations between Charpy impact properties and microstructure, Owen, Whitmore, Cohen and Averbach⁶ deduced that effects attributable to banding were insignificant compared with those attributable to other microstructural parameters. The present experiments were prompted by a desire to obtain more direct information on this elusive subject.

Since the ferrite-pearlite banding lies parallel to the rolling direction, a correlation between such banding and the anisotropic properties of hot-rolled plate might be expected. Directional effects are most apparent in notch-bar impact tests.⁷ Troiano and Klinger⁸ used a V-notch Charpy test to study the directionality of mechanical properties in hot-worked steels and concluded that there is no directional effect in the brittle range (below the 10 ft-lb level), ductility being the only basic property that exhibits an isotropy. Jarczok, Girardi and Rowland⁹ showed that the only property improved by homogenizing

a banded 4340 steel was the transverse ductility, and the resultant improvement was commercially insignificant.

PRODUCTION OF RANDOM FERRITE-PEARLITE STRUCTURES

All of the experiments were performed on a semikilled ABS Class B steel supplied in the form of 3/4-in. hot-rolled plate. The analysis and room temperature mechanical properties are given in Table 1.

TABLE 1

CHEMICAL COMPOSITION AND ROOM TEMPERATURE PROPERTIES OF THE AS-RECEIVED PLATE

<u>C</u>	<u>Mn</u>	<u>P</u>	<u>S</u>	<u>Si</u>	<u>Cu</u>	<u>Al</u>
0.16	0.69	0.014	0.028	0.022	0.028	0.042
<u>Elastic Limit</u>		<u>Upper Yield Point</u>		<u>Lower Yield Point</u>		
<u>(10³ psi)</u>		<u>(10³ psi)</u>		<u>(10³ psi)</u>		
22.0		33.0		31.0		
<u>Elongation</u>		<u>Reduction in Area</u>				
<u>(per cent)</u>		<u>(per cent)</u>				
30.9		58.2				

In accordance with previous work on this steel, two parameters were used to describe the degree of the banding: (a) the ratio of the average pearlite linear intercept, β , measured parallel and perpendicular to the rolling surface, and (b) the ratio of a mean ferrite path, α_2 , measured in the same two directions. α_2 is the mean ferrite intercept made by

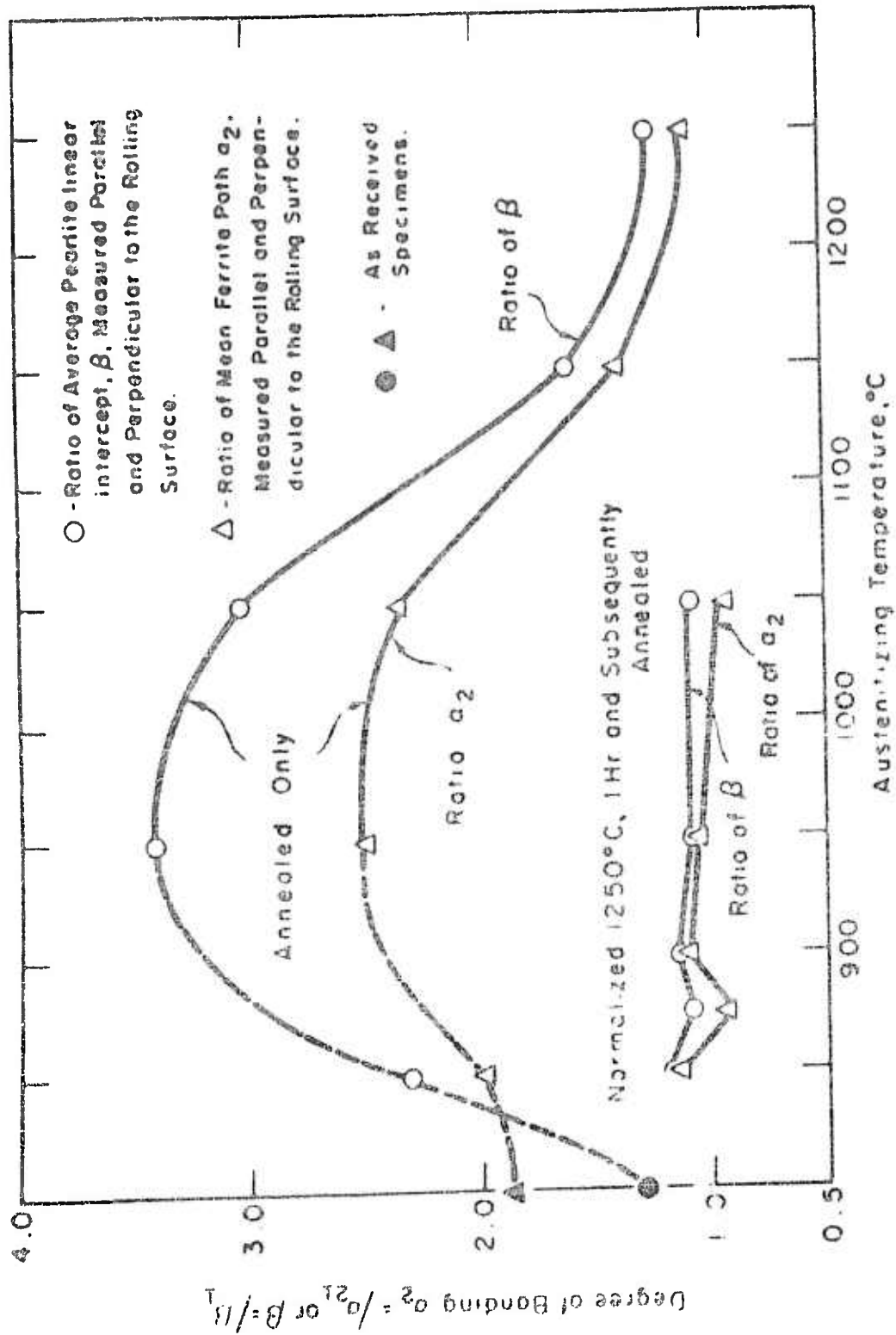


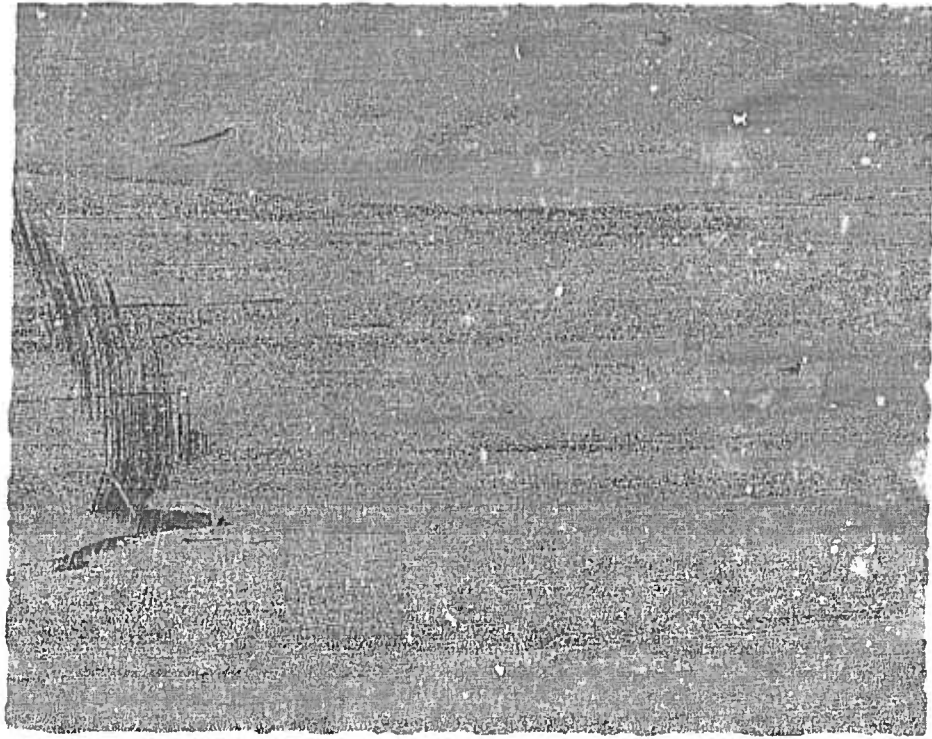
FIG. 1- THE EFFECT OF HEAT TREATMENT ON THE SEVERITY OF BANDING AS REVEALED BY TWO DIFFERENT MICROSCOPIC PARAMETERS.

the ferrite-pearlite boundaries along straight-line transverses, the ferrite-ferrite boundaries being ignored. The measurements were conducted on sections transverse to the rolling direction.

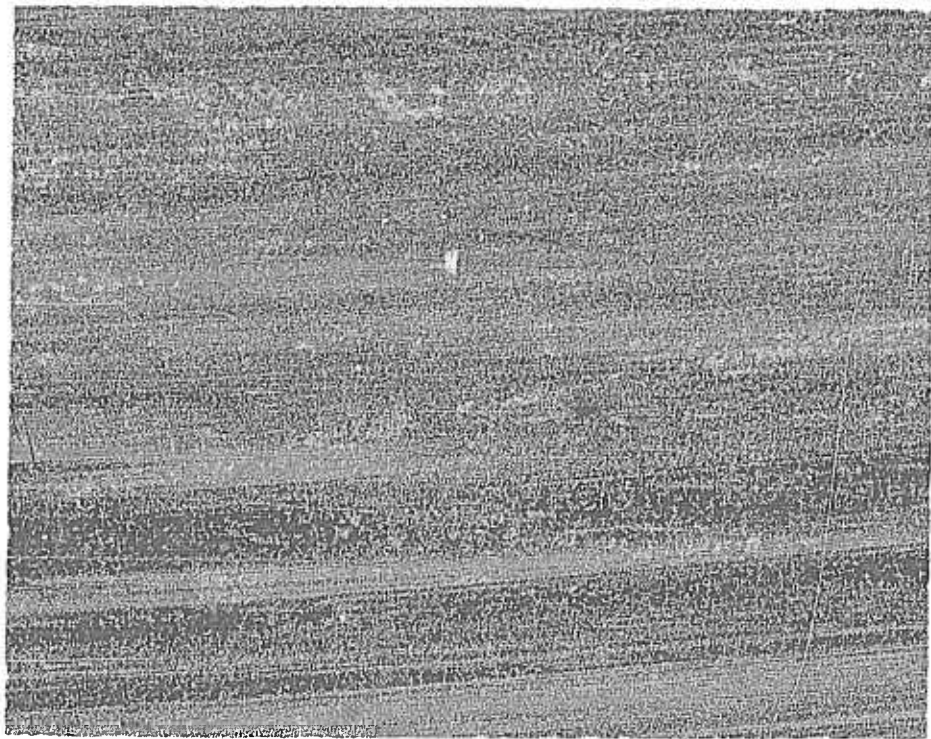
In hypo-eutectoid steels, the metallographic banding pattern is established during the pro-eutectoid separation of ferrite and the resulting segregation of the carbon in the pearlite-rich regions. Thus it is not surprising that both the austenitizing temperature and the cooling rate have a pronounced effect. The former effect is shown by the data in Fig. 1. In this series, all the annealing treatments were carried out with the same slow cooling rate (about 1.5 C/min), and the banding was found to be a function of the austenitizing temperature, the severity increasing from 850 to 900 C and then decreasing as the temperature was further increased above 1050 C. The initial increase may be irrelevant because it depends only upon the low value obtained at 850 C, and from other experience with this steel it is suspected that this temperature is slightly below A_3 . After annealing for 1 hour at 1250 C, the banding was almost completely eliminated.

The as-received specimen was less severely banded than those annealed between 900 and 1050 C (Fig. 1). This is probably due to the fact that the cooling rate of the plate from the rolling temperature was somewhat faster than that of the annealed specimens. An example of the effect of cooling rate is shown in Fig. 2 in which the microstructure on transverse sections of a specimen furnace cooled (1.5 C/min) from 950 C is compared with that of a specimen air cooled (150 C/min) from the same temperature.

Jatczak, Girardi and Rowland,⁹ studying alloy steels, concluded that chemical heterogeneity is the primary cause of banding. Ignoring the 850 C point in Fig. 1, the decrease in banding with increase in austenitizing temperature is consistent with this view. Further, it was found that the extent to which banding was reduced by annealing at a high austenitizing temperature was a function of the time at temperature. To show the time effect, it was necessary to use



Transverse (a) 100X
950°C - 1 Hr. Furnace Cool



Transverse (b) 100X
950°C - 1 Hr. Air Cool

Figure 2. Effect of Cooling Rate on Distribution of Ferrite.

a method of developing banding suggested by the treatments of Jarczak et al.⁹ After austenitizing at the temperature under investigation, the specimen was air cooled to room temperature and then reheated to 900--950 C, which is the temperature range most favorable for the development of banding. After 1 hour at 900 C, the specimen was cooled to a temperature in the two-phase region and held for an hour, after which it was quenched. By trying various final temperatures, it was established that the banding owing to the carbon re-distribution could be seen most clearly when 750 C was employed. Finally, the specimens were tempered at 350 C for 1 hour

In Fig. 3, microstructures are shown of specimens that had been normalized at 0, 1 and 2 hours at 1250 C before being given the special treatment. The banded structure breaks up progressively as the time at 1250 C is increased, but even after 2 hours some evidence of banding can be seen. It was found that 24 hours at temperature was required to eliminate all evidence of heterogeneity.

Further support for the view that the main function of the 1250 C treatment is to homogenize the distribution of alloying elements was provided by a series of experiments in which, after a normalizing treatment for 24 hours at 1250 C, the specimens were given prolonged treatments at lower austenitizing temperatures with the objective of causing the banding to return, if possible.

In one series, the specimen was cooled from 1250 C to a temperature of 950 C, and this was maintained for as long as 24 hours before the specimen was slowly cooled to room temperature. In another sequence, the specimen was air cooled from 1250 C to room temperature before being re-annealed at 950 C for times up to 24 hours. No treatment was found that produced any evidence of banding.

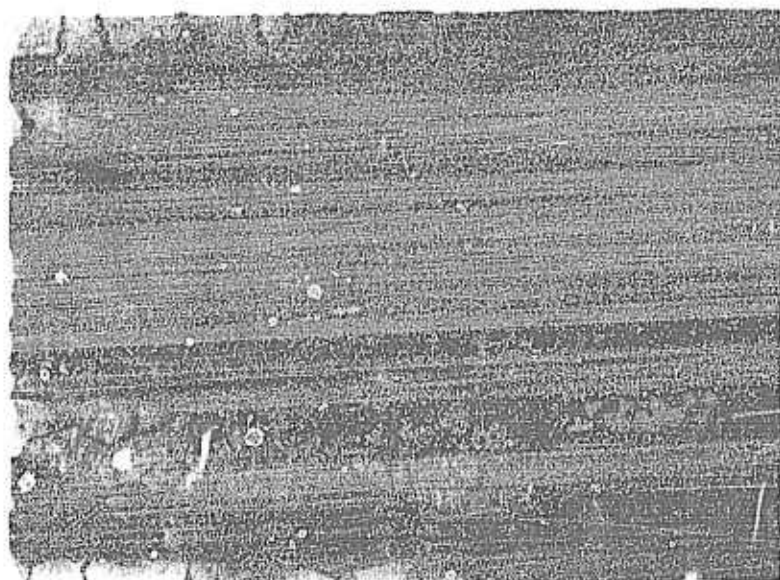
During the course of the exploratory work that led to the adoption of this treatment, a further complicating effect was encountered. It was found that, when the 1250 C homogenizing temperature was followed by annealing at temperatures below 1050 C, there was a pronounced tendency for the ferrite to develop



0HR - 1250°C A.C.
(a) 900°C - 1 Hr. F. C;
750°C - 1 Hr. W.Q.
350°C - 1 Hr. A.C.
Transverse 100X



1 Hr. - 1250°C A.C.
(b) 900°C - 1 Hr. F.C;
750°C - 1 Hr. W.Q.
350°C - 1 Hr. A.C.
Transverse 100X



2 Hr. - 1250°C A.C.
(c) 900°C - 1 Hr. F.C;
750°C - 1 Hr. W.Q.
350°C - 1 Hr. A.C.
Transverse 100X

Figure 3. Effect of Time at 1250°C on Ferrite-

a mixed grain size. An example of this is shown in Fig. 4. However, this tendency became less marked with faster cooling rates from the homogenizing temperature and was very slight after air cooling. To ensure a homogeneous ferrite grain size, oil quenching from the 1250 C treatment was adopted.

INFLUENCE OF BANDING AND SPECIMEN ORIENTATION ON NOTCH IMPACT PROPERTIES

In the Charpy tests, the severely banded steel (annealed 950 C, see Fig. 5 (a) and (b)) was compared with specimens that had been homogenized before the 950 C annealing, the treatment being:

1250 C, 24 hours, oil quench

950 C, 1 hour, furnace cool

The microstructure is shown in Fig. 6 (a) and (b). A quantitative comparison of the two structures is given in Table 2. In all respects other than the distribution of ferrite and pearlite, the two structures are nearly identical.

Charpy blanks were machined from the center thickness of the plate. Four sets of specimens were prepared, two with the major axis parallel to the rolling direction and two in the transverse direction. Half of the specimens of one orientation were machined with the notch parallel to the plate surface, the other half having the notch normal to the plate surface. The different orientations of specimen axis and notch, with the symbols used to distinguish them, are shown in Fig. 7.

Charpy transition curves were determined using at least thirty specimens for each curve. The curves for longitudinal specimens in the banded and unbanded conditions are shown in Fig. 8, and the corresponding curves for specimens cut transversely to the rolling direction in Fig. 9. In Fig. 10 (a) and (b), the four curves for each condition are assembled. The fracture appearance, estimated visually, is plotted as a function of the testing temperature in Fig. 11.

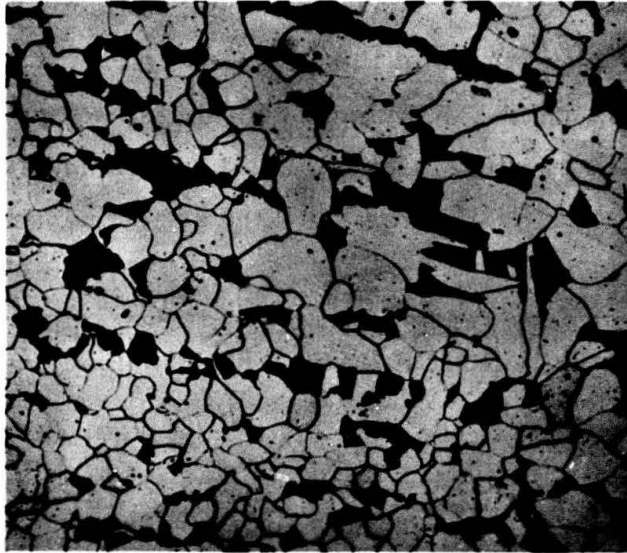


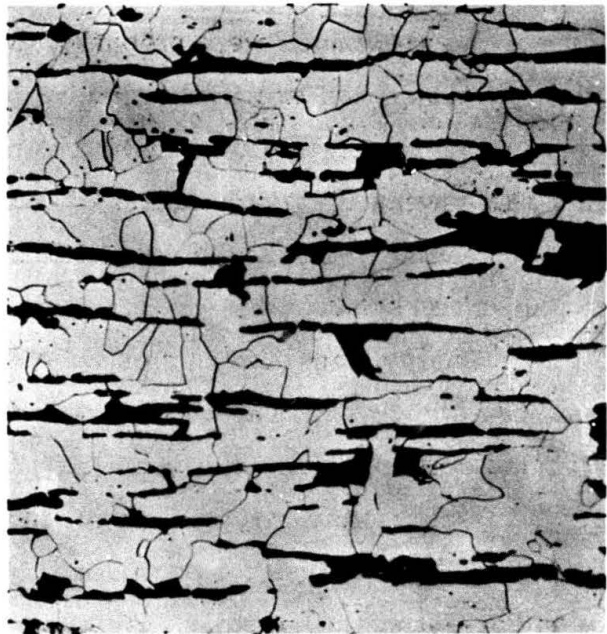
Figure 4.

100X

Mixed ferrite grain size. Specimen heat treated 1250°C, 1 hr., furnace cooled. 875°C, 1 hr., furnace cooled.



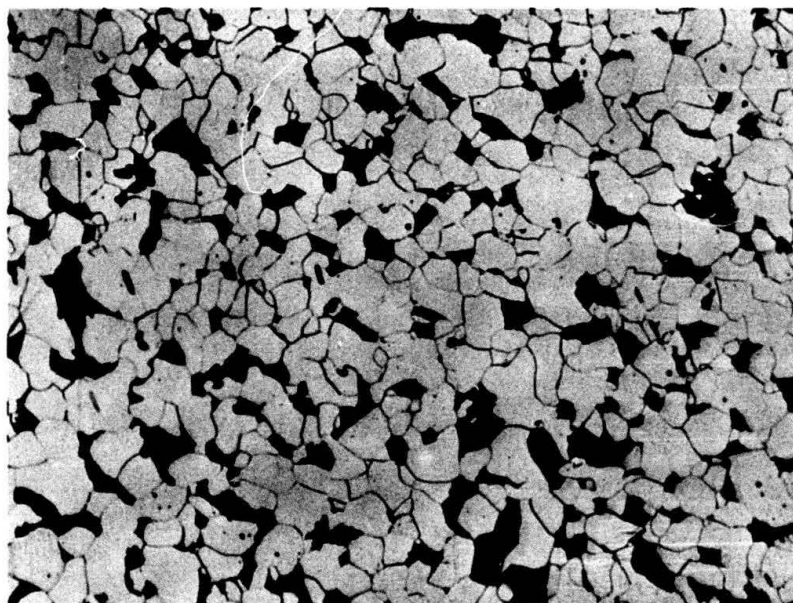
(a)



(b)

Figure 5. (a) Longitudinal and (b) Transverse Sections.

Heat treated 950°C, 1 Hr., furnace cooled. 100X



(a)

100X

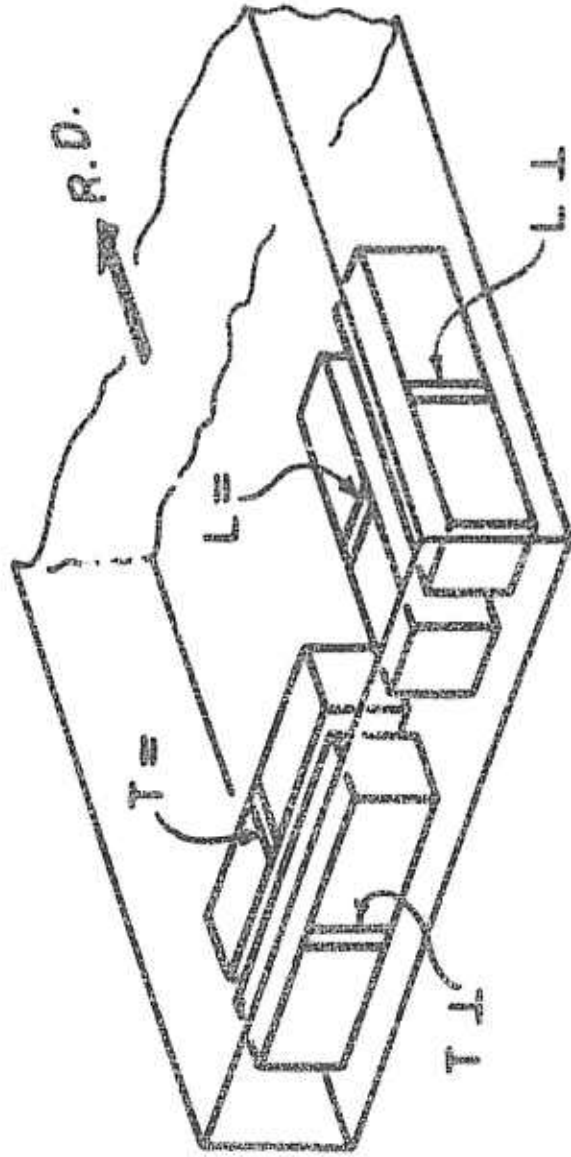


(b)

100X

Figure 6. (a) Longitudinal and (b) Transverse Sections

Heat treated 1250°C, 24 hrs., oil quenched
950°C, 1 hr., furnace cooled



- ▬ Notch parallel to rolling surface. \perp Notch perpendicular to rolling surface.
- L Specimen axis parallel to rolling direction. R.D. Rolling direction
- T Specimen axis perpendicular to rolling direction.

FIG. 7- ORIENTATION OF SPECIMEN AXIS AND NOTCH.

When a low energy-level criterion was adopted, there was no significant difference in the transition temperature between specimens of different axis or notch orientation or between the banded and unbanded steel. For example, the 10 ft-lb transition temperature was virtually unaffected by any of the geometric or microstructural variables introduced into these experiments. However, in the high energy part of the curve, where the energy absorption is mainly due to the formation of a fibrous crack, both banding and orientation are factors

The energy curves for the specimens with the notch parallel to the rolling surface were higher in the ductile range than those with the perpendicular notch. In transverse specimens, this difference was unaffected by homogenization but, in specimens with the major axis in the longitudinal direction, the notch-direction effect was reduced. Among specimens of the same notch direction, the longitudinal specimens in the high energy range were appreciably more ductile than those cut transversely to the rolling direction. This directional effect persisted in the homogenized specimens (Figs. 8, 9 and 10). Removal of the microscopic banding had a marked influence on the levels of energy absorption at the top end of the temperature range (Figs. 8 and 9); the homogenized specimens, although still anisotropic, had higher energy values than did those in the banded condition. This increase in the high energy level and the constancy of the energy absorption in the lower temperature range resulted in a decrease in transition temperature of transverse specimens upon homogenizing when an energy criterion greater than 20 ft-lb was adopted. This is illustrated by the transition temperatures at 10 ft-lb and 50 ft-lb listed in Table 3.

The fracture appearance curves are subject to an appreciable error that is difficult to assess. However, it is thought that the uncertainty is insufficient to invalidate the subsequent discussion. As with the energy curves, neither the distribution of the ferrite and pearlite nor the orientation of the specimen had any effect in the temperature range in which the fracture was mainly cleavage, i.e.

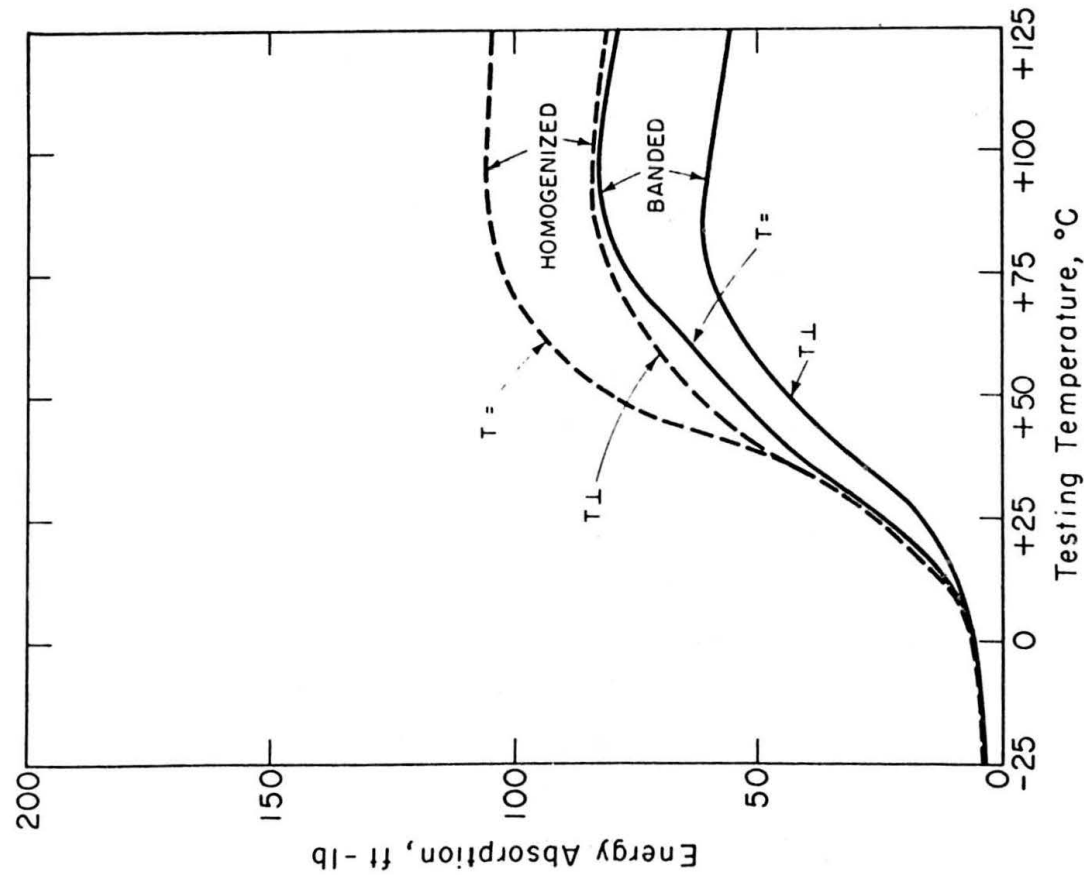


FIG.9 - EFFECT OF HOMOGENIZATION ON THE CHARPY PROPERTIES OF SPECIMENS WITH SPECIMEN AXIS PERPENDICULAR TO THE ROLLING DIRECTION.

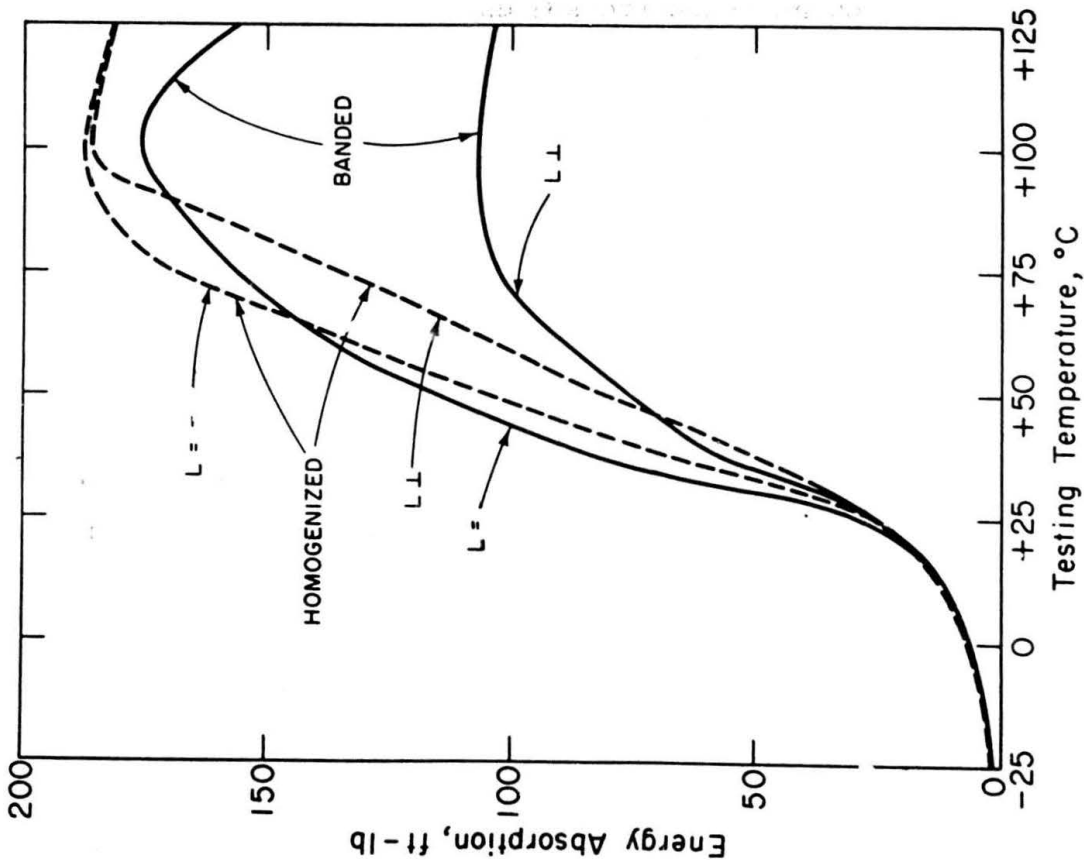


FIG.8 - EFFECT OF HOMOGENIZATION ON CHARPY PROPERTIES OF SPECIMENS WITH SPECIMEN AXIS PARALLEL TO THE ROLLING DIRECTION.

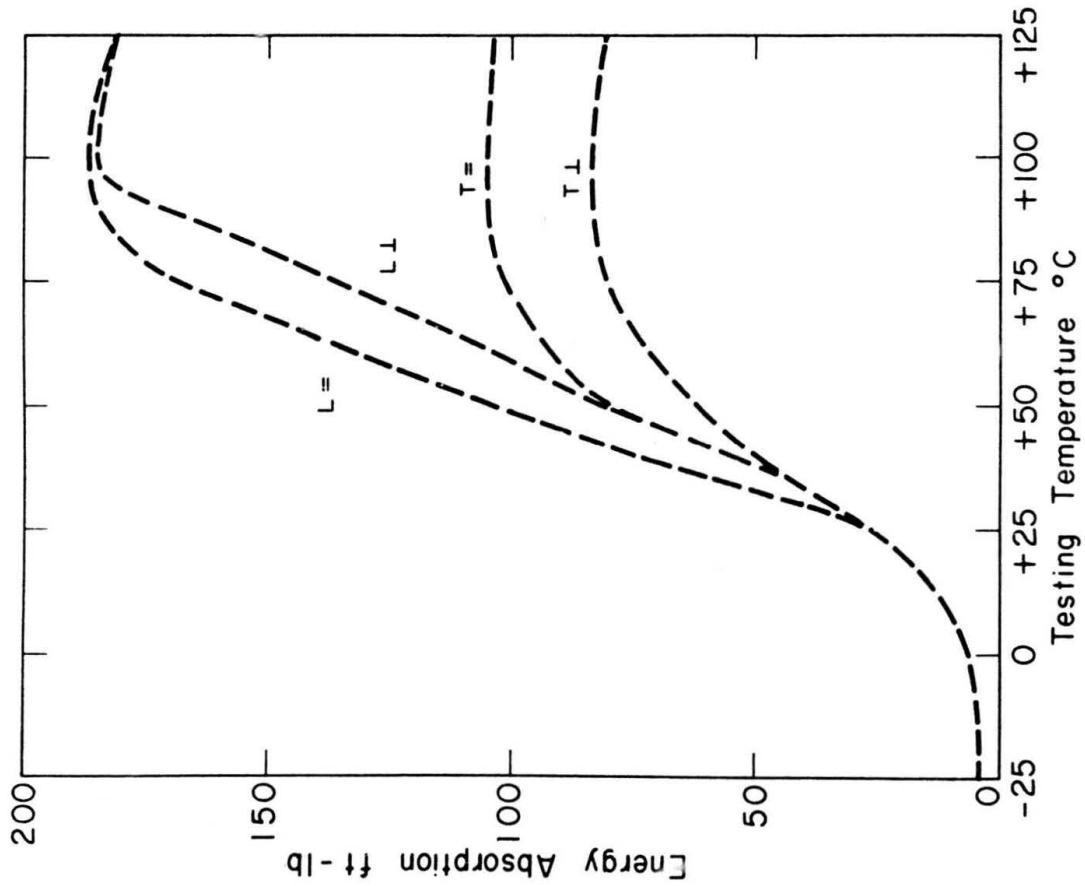


FIG. 10b EFFECT OF SPECIMEN AND NOTCH ORIENTATION ON THE CHARPY PROPERTIES OF THE HOMOGENIZED STEEL

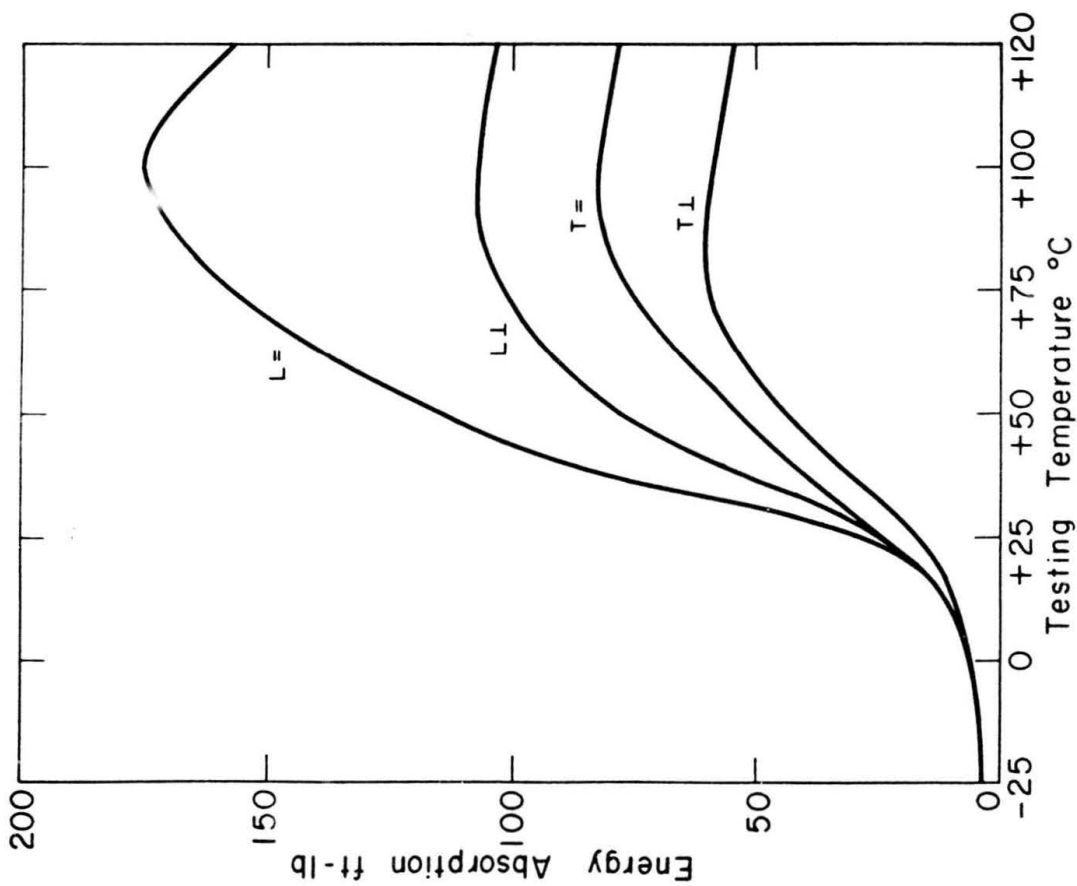


FIG. 10a EFFECT OF SPECIMEN AND NOTCH ORIENTATION ON THE CHARPY PROPERTIES OF THE BANDED STEEL

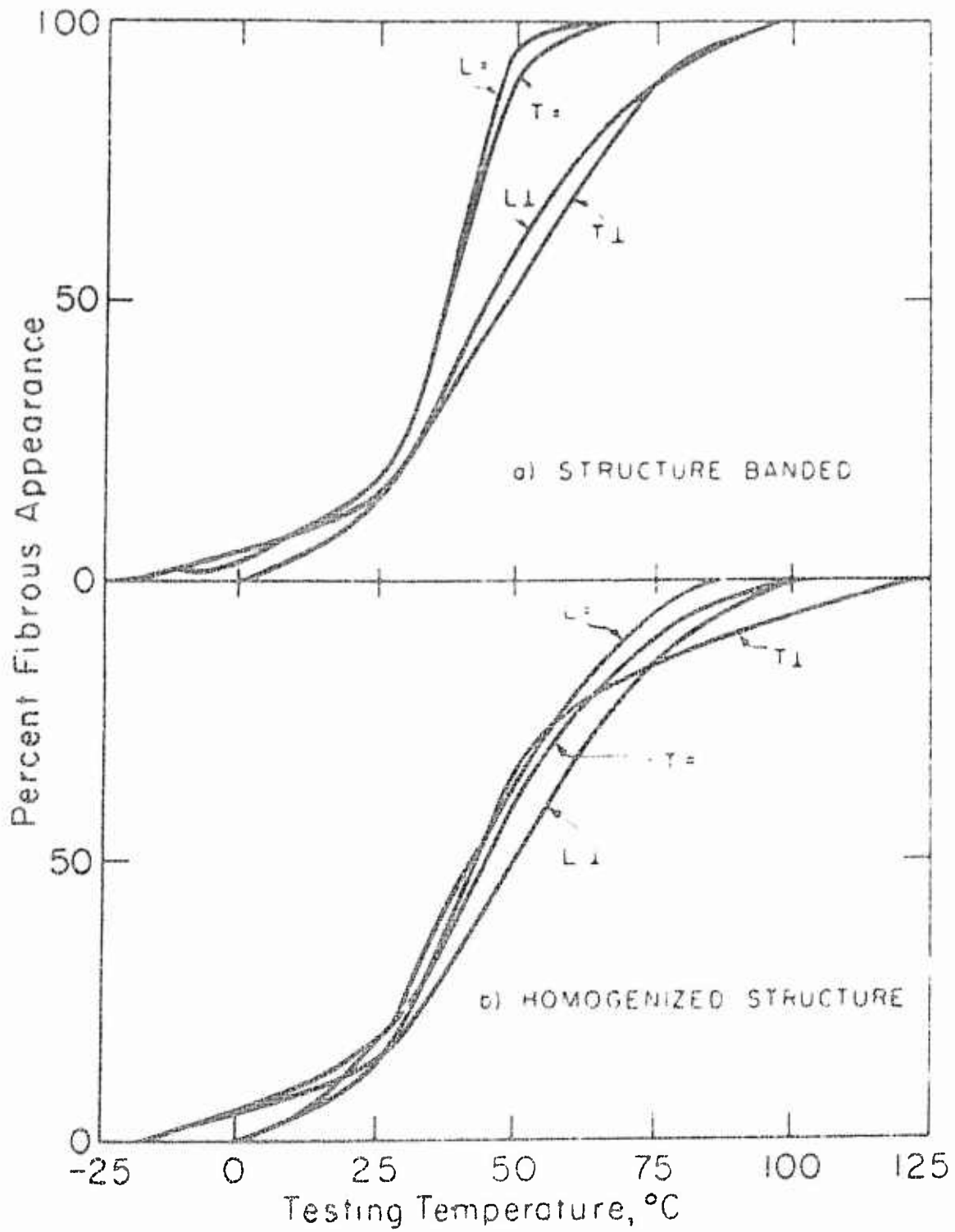


FIG. II- EFFECT OF HOMOGENIZATION ON THE FRACTURE APPEARANCE

TABLE 2

Parameter	Transverse Section			Longitudinal Section		
	950 C, 1 hr, FC	1250 C 24 hr OQ	950 C 1 hr FC	950 C 1 hr FC	1250 C 24 hr OQ	950 C 1 hr FC
Vol. fraction of ferrite, %	83	87	85	85	86	86
Vol. fraction of pearlite, %	17	13	15	15	14	14
Mean ferrite grain diameter mm	0.072	0.071	0.077	0.077	0.067	0.067
Number of ferrite grains per mm ³	5360	5360	4150	4150	6160	6160
A. S. T. M. No.	5.0	5.0	4.9	4.9	5.2	5.2
Pearlite Banding parameter, $\beta = \beta \perp$	3.42	1.03	3.43	3.43	1.02	1.02
Ferrite Banding parameter, $\gamma_2 = \gamma_2 \perp$	2.49	0.96	3.45	3.45	1.16	1.16

FC - furnace cool

OQ - oil quench

TABLE 3

THE EFFECT OF HEAT TREATMENT ON THE
TRANSITION TEMPERATURE AT TWO ENERGY LEVELS

<u>Direction</u>	<u>Transition Temperature at 10 ft-lb (C)</u>	<u>Transition Temperature at 50 ft-lb (C)</u>
<u>950 C, 1 hr, FC</u>		
L =	11	32
L⊥	11	35
T =	11	45
T⊥	15	60
<u>1250 C, 24 hr, QQ followed by 950 C, 1 hr, FC</u>		
L =	9	32
L⊥	9	38
T =	9	38
T⊥	9	39

below about 20 per cent fibrous appearance. However, in the banded condition, the fracture appearance curves revealed an anisotropy that, unlike the effects shown by the energy curves, was removed by homogenizing. A further surprising feature was the apparently dominant effect of notch direction in the banded specimens, those with notches parallel to the surface having appreciably lower 100 per cent fibrous transitions than those with normal notches. This contrasts sharply

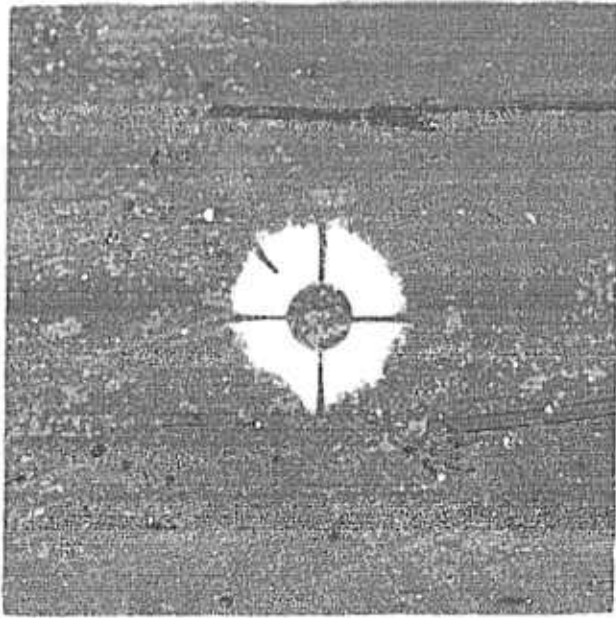
with the energy curves, where the direction of the specimen axis relative to the rolling direction was at least as important as the notch direction.

DISCUSSION

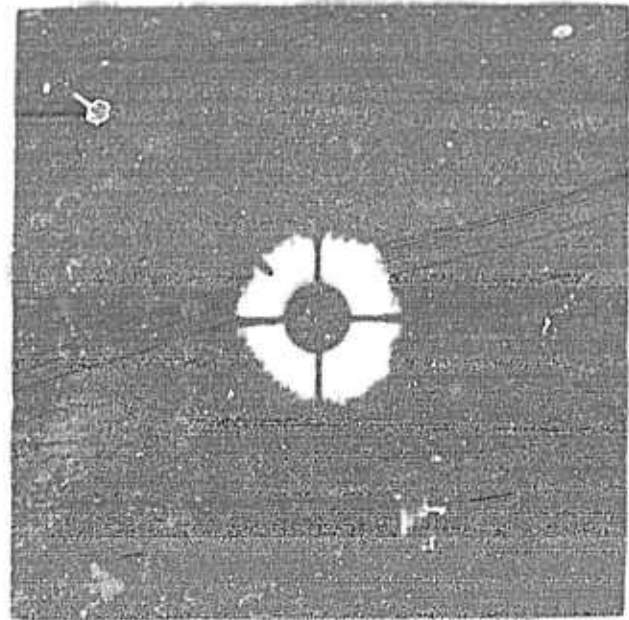
No experimental evidence was found to support the theoretical ideas predicting an effect of structure lamination on the brittle fracture properties. However, the Charpy test, in which the propagation of the fracture is an important feature, may not be the most suitable means of assessing the magnitude of properties that are mainly associated with fracture initiation. Possibly low temperature, round-bar tensile tests would be more informative.

In the temperature range in which the crack is predominantly fibrous, the increase in energy absorption on homogenizing is in accord with earlier observations.^{8,9} Since this increase coincides with the disappearance of ferrite-pearlite banding, it is tempting to assume a cause and effect relationship. However, the persistence of directional effects suggests that the factors involved are more subtle than those revealed by microscopic examination.

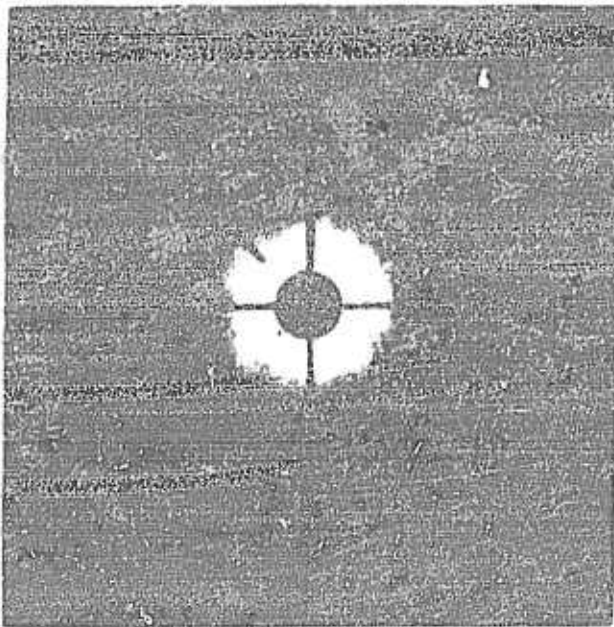
Although previous investigators⁷ have failed to disclose any preferred crystallographic orientation in the ferrite in hot-rolled plate, it was thought that if a more sensitive x-ray method for its detection could be devised, a relatively slight texture might be found to account for the anisotropic behavior. The ferrite grain size of most hot-rolled plate is such that, with stationary film and specimen back-reflection x-ray techniques, spotty and discontinuous Debye-Scherrer rings are obtained. To improve this situation, a moving specimen arrangement was devised by which the crystals from at least forty different locations on the specimen surface contributed to each Debye-Scherrer ring. Banded and homogenized specimens in both longitudinal and transverse directions were examined by this technique. Representative diffraction patterns are shown in Fig. 12. No evidence of a marked preferred orientation was found.



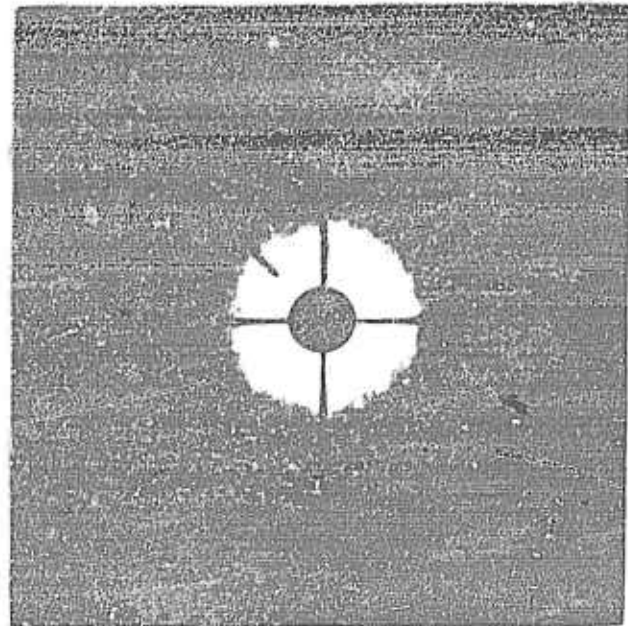
(a)



(c)



(b)



(d)

Figure 12 (a),(b) X-ray back reflection patterns from specimen heat treated 950°C , 1 hr., furnace cooled, banded structure. (a) longitudinal, (b) transverse section.

(c),(d) Patterns from specimens heat treated 1250°C , 24 hrs., oil quenched and 950°C , 1 hr., furnace cooled, homogeneous microstructure. (c) longitudinal, (d) transverse section.

Other theories to account for the directional effect have postulated the alignment of defects, either slag inclusions or submicroscopic cracks, by the rolling operation. Tipper⁷ has demonstrated the inadequacy of the submicro-crack concept. The role of inclusions warrants further consideration. Hot rolling produces laminations of non-metallics that are parallel to the ferrite banding. Homogenizing heat treatment can remove the chemical segregation and the ferrite banding but does not alter the distribution of inclusions. The present results can be explained if it is assumed that (1) inclusions and ferrite-pearlite laminations do not significantly alter the energy absorption of an intersecting cleavage crack, (2) both types of lamination decrease the energy absorption of a fibrous crack, but the effect of inclusions is much greater than that of the ferrite-pearlite banding, and (3) the distribution of inclusions does not affect the microscopic proportion of fibrous appearance in the fracture. The energy increase in the ductile range on homogenizing could be attributed to the re-distribution of ferrite and pearlite, and the persistence of the directional effect to the stability of the non-metallics. The third assumption is necessary to explain the apparent discrepancy between the change in energy absorption and the proportion of fibrous appearance with orientation and temperature. However, the experimental data relating to fracture appearance are unsubstantial, and it would be unwise to elaborate these ideas without further experimental support.

CONCLUSIONS

1. Ferrite banding in reheated hot-rolled mild steel is influenced by the austenitizing temperature, the time at temperature, and the cooling rate.
2. Once the banding has been completely removed by an homogenizing heat treatment, it is not reformed by thermal treatment.
3. The experimental data are consistent with the view that banding is a result of chemical heterogeneity, although the segregating elements were not identified in this investigation.

4. The brittle fracture properties as revealed by the Charpy test (that is, behavior below the 20 ft-lb or about 20 per cent fibrous appearance level) are not affected by the extent of ferrite-pearlite laminations, nor do they show any anisotropy even in severely banded plates.

5. The fibrous fracture properties are influenced by specimen and notch orientation, as well as by subsequent heat treatment, to a pronounced degree. At a selected testing temperature in the ductile range, both the longitudinal and transverse energy absorption is increased by an homogenizing heat treatment which removes the ferrite-pearlite banding. However, the anisotropy persists. The experimental evidence suggests that, when judged on the basis of fracture appearance only, the notch direction is important, but this directional effect is erased by the homogenizing treatment.

6. Preferred crystallographic orientation of the ferrite is not a factor in these phenomena.

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