SSC-128

AD 239 049

INFLUENCE OF STEEL-MAKING VARIABLES ON NOTCH TOUGHNESS

J.H. van der Veen

Royal Netherlands Blast Furnaces and
Steelworks. Ijmuiden, Holland

27 June 1960

SSC-128

INFLUENCE OF STEEL-MAKING VARIABLES ON NOTCH TOUGHNESS

by

J. H. van der Veen

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.

June 27, 1960

Dear Sir:

At its annual meeting in March, 1960, the Committee on Ship Steel enjoyed as its guest speaker Dr. J. H. van der Veen of the Royal Netherlands Blast Furnaces and Steelworks. His topic of "Influence of Steel-Making Variables on Notch Toughness" provided a description of present practices in the Netherlands and much background on their current thinking.

The enclosed report, containing the written version of Dr. van der Veen's presentation, is being distributed by the Ship Structure Committee to concerned individuals and groups.

Please send any comments on this report to the Secretary, Ship Structure Committee.

Sincerely yours,

E H Thiele

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

Serial No. SSC-128

Special Report

on

INFLUENCE OF STEEL-MAKING VARIABLES ON NOTCH TOUGHNESS

by

J. H. van der Veen
Royal Netherlands Blast Furnaces
and Steelworks
Ijmuiden, Holland

Washington, D. C.
National Academy of Sciences--National Research Council
June 27, 1960

CONTENTS

INTRODUCTION

The effort to produce mild-steel plates with improved resistance to brittle fracture has led to some experience with regard to the influence of various process factors on notch toughness. Improved steels can be made, using the knowledge derived from this experience, by controlling one or more of these factors. The effects of the various factors seem to be additive, so that the best results are obtained by keeping all of the known variables at their optimum levels.

The relative importance of the process variables seems to be dependent on the test criterion chosen. one variable, for example, would mainly improve fracture appearance, whereas another would mainly affect impact energy. This divergence of effect between process variables would explain the lack of correlation between different test-criteria in comparing plates that have been processed in different ways. For plates having intermediate quality with regard to notch toughness, this point is especially important, since in obtaining this quality usually only one or two of the known process factors are controlled in order to obtain the required properties. In other words, intermediate quality plates may be made in different ways; which way should be chosen by the steelmaker? The answer to this question depends to a large extent on the choice of test criterion. This choice, however, is still different for different users and classification societies, because apparently insufficient common knowledge exists about the correlation between test criteria and service behavior. Further investigation in this field would seem to be very necessary, especially since the best way to classify steels should be based, in my opinion, on requirements that can be measured on the finished product. Specification of manufacturing process by the user should be avoided because this may lead to uneconomic production and may not always be sufficiently adequate. Examples supporting this view will be given in some of the following paragraphs.

PROCESS VARIABLES

The following process variables will be discussed

-chemical analysis (especially manganese and carbon content)

Influence of Mn content on Charpy V impact properties of semi-killed ship plate

Production figures from 105 plates from 65 casts

Normal rolling practice finishing temperature see below

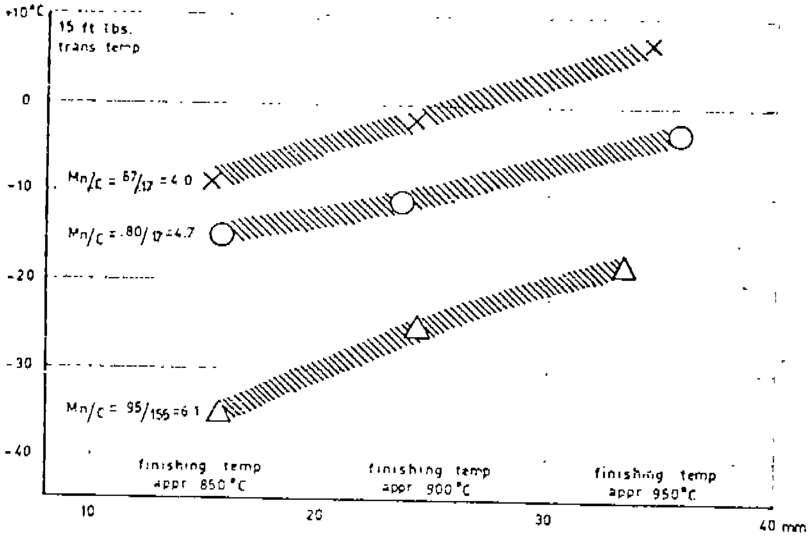


fig 1

Influence of Mn content on Charpy V impact properties of semi-killed ship plate

Production figures from 105 plates from 65 casts

Normal rolling practice, finishing temperature see below

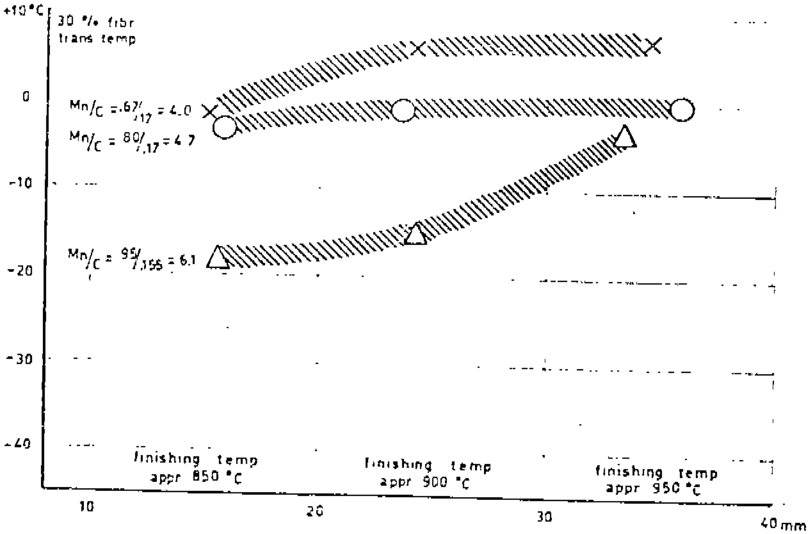


fig 2

-plate thickness

-finish-rolling temperature (controlled-rolling practice)

-deoxidation (semikilled versus Al-killed)

-normalizing

-cross rolling

Mn/C RATIO AND THICKNESS

The influence of Mn/C ratio and thickness on Charpy-V test results is shown in Figs. 1 and 2. These results apply to semikilled (balanced) ship steel, rolled according to normal rolling practice. Finishing temperatures have not been measured for individual plates. The plates concerned were taken from current production; 65 casts and 105 plates were involved. The Mn content varied between 0.60 and 1.15%. The results obtained have been divided into three groups of Mn content: 0.60-0.70, 0.75-0.85 and 0.87-1.15%. Each of these groups has been divided into three thickness groups. Further details can be seen from Table , from which the Figs. 1 and 2 were made. The Charpy tests were taken parallel to the direction of rolling.

Figure 1 shows that the 15 ft-lb transition temperature increases with increasing thickness for all of the three average Mn contents. This effect is due to coarsening of the grain, caused by the increase of finishing temperature and the decrease of cooling velocity after rolling, when the thickness is increased. The favorable influence of high manganese on the 15 ft-lb transition temperature is clearly shown. For the three thickness groups in this particular investigation, this temperature is decreased by about 25 C when Mn is raised from average 0.67% to 0.95%.

Figure 2 shows the influence of Mn and thickness, for the same collection of plates, on the 30% fibrous-transition temperature. The average overall effects of Mn and thickness on this criterion appear to be smaller. Further, it would seem that the favorable influence of high Mn, in this case, is not independent of thickness: the effect is smaller for the thickest batch of plates.

TABLE 1 (see Figs. 1 and 2)

THE INFLUENCE OF Mn CONTENT AND PLATE THICKNESS ON CHARPY IMPACT PROPERTIES FOR SEMIKILLED SHIP STEEL UNDER NORMAL ROLLING PRACTICE

Number of plates	Number of charges	Finishing rolling temp. (appr.) °C	Plate thickness mm	Ultimate Strength kg/mm²	Per Cent elong. on 8 in.	C %	Mn %	P %	S %	Si %	Trans. temp. 15 ft-lb °C	Trans. temp. 30% fibr. °C
			Medium Manganese									
19	12	850	lowest 14	42	24	.15	.64	.011	.026	.03	-9	-2
			average 15.3	45	28	.166	.671	.0171	.0355	.041		
			highest 17.5	47	35	.18	.70	.030	.045	.05		
17	14	900	lowest 22	41	25	.15	.60	.010	.022	.03	-2	+6
			average 24.1	43	29	.170	.67	.016	.034	.04		
			highest 28	45	35	.18	.70	.033	.046	.05		
6	6	950	lowest 32	41	29	.15	.62	.018	.022	.02	+7	+7
			average 34.5	43	30	.173	.663	.028	.034	.04		
			highest 38	44	35	.19	.70	.045	.044	.05		
			High Manganese									
15	11	850	lowest 13	42	23	.13	.75	.008	.022	.03	-15	-3
			average 15.8	45	28	.163	.786	.021	.033	.04		
			highest 19	48	36	.18	.84	.053	.050	.05		
11	8	900	lowest 22	43	23	.16	.75	.014	.026	.03	-11	-1
			average 23.6	46	27	.190	.788	.023	.036	.04		
			highest 27.5	49	34	.20	.84	.029	.050	.05		
3	3	950	lowest 35	42	25	.17	.76	.016	.026	.03	-3	0
			average 36	45	28	.178	.76	.023	.038	.04		
			highest 38	47	32	.19	.76	.027	.050	.05		
			Very High Manganese									
20	17	850	lowest 14	42	23	.14	.89	.014	.024	.03	-35	-18
			average 15.6	47	27	.156	.985	.017	.029	.04		
			highest 19	49	32	.19	1.15	.022	.035	.05		
11	7	900	lowest 22	43	25	.14	.90	.014	.024	.02	-25	-15
			average 24.3	45	28	.152	1.00	.017	.029	.03		
			highest 28	48	32	.17	1.08	.021	.035	.04		
3	3	950	lowest 32	42	27	.14	.87	.018	.024	.03	-18	-3
			average 33.3	44	29	.153	.95	.024	.033	.04		
			highest 35	46	31	.16	1.08	.033	.038	.04		

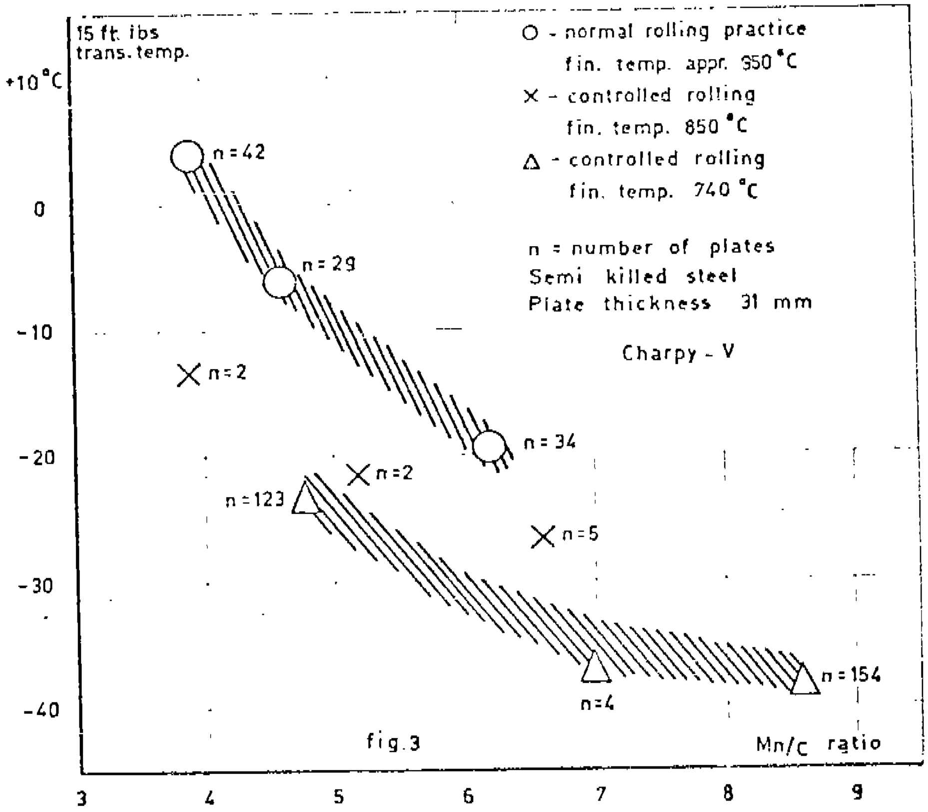


fig.3

Mn/C RATIO AND CONTROLLED ROLLING

Figures 3--7 show the influence of Mn and controlled rolling on Charpy V-notch and slow notch-bend-transition temperatures. The influence of plate thickness was eliminated by converting the available data to a plate thickness of 31 mm. This was done by interpolation, using graphs of transition temperature against thickness. The results were obtained on semikilled steel. The Charpy tests were taken parallel, the slow notch-bend tests perpendicular to the direction of rolling. Further details of the plates concerned may be seen in Table 2.

The graphs clearly show that both high manganese and controlled low-finishing have a beneficial influence on notch toughness. However, there is a marked difference with regard to the relative importance of the effects, dependent on which test criterion is used.

TABLE 2

THE INFLUENCE OF Mn AND FINISHING ROLLING TEMPERATURE ON CHARPY V-NOTCH AND SLOW NOTCH-BEND (SNB) PROPERTIES OF SEMIKILLED STEEL (PLATE THICKNESS 31 MM).

	Number of plates	Mn/C ratio	Remarks
1. Normal rolling practice fin. temp. appr. 950 C	42	3.9	15 ft-lb, 35 ft-lb, 30% fibr., 50% fibr. trans. temp. for a plate thickness of 31 mm were deduced from production data by interpolation.
	29	4.6	
	34	6.2	
			Slow Notch-Bend trans. temp. (see ad 1).
2. Controlled rolling fin. temp. 850 C	2	3.9	Data from a limited investigation on the influence of the finishing temperature (see ad. 2).
	2	5.2	
	5	6.6	
3. Controlled rolling fin. temp. 740 C	123	4.8	Trans. temp. for a plate thickness of 31 mm were deduced from production data by interpolation.
	154	8.6	
	4	7.0	Data from a limited investigation on the influence of the finishing temperature (see ad. 3).

	Number of plates	Mn/C ratio	32 mm fibrous SNB test	15 ft-lb	35 ft-lb	30% fibr.	50% fibr.
ad. 1	1	3.6	40	(Six high-finished plates from the Royal Dutch Steelworks sent to the SSC in Dec. 1957. From these data the 32-mm fibr. trans. temp. in the SNB test were deduced for a plate thickness of 31 mm by interpolation.)			
plate thickness 38 mm	1	4.7	27				
	1	7.7	26				
	1	4.1	30				
plate thickness 19 mm	1	4.7	6				
	1	7.3	-3				
ad. 2	1	4.0	30	-11	3	9	21
	1	3.8	17	-16	1	8	22
	1	5.3	9	-30	-24	-10	3
	1	5.1	16	-13	6	10	23
plate thickness 31 mm	1	7.1	-1	-20	-11	-19	-4
	1	6.1	-22	-20	- 8	-19	-10
	1	6.5	-3	-30	-16	-25	-11
	1	6.9	-1	-33	-19	-24	-11
	1	6.6	--	-30	-20	-24	-11
ad. 3	1	7.3	-20	-28	-19	-29	-17
plate thickness 31 mm	1	6.6	-26	-48	-37	-40	-27
	1	7.5	-23	-31	-16	-30	-20
	1	6.4	--	-42	-32	-40	-32

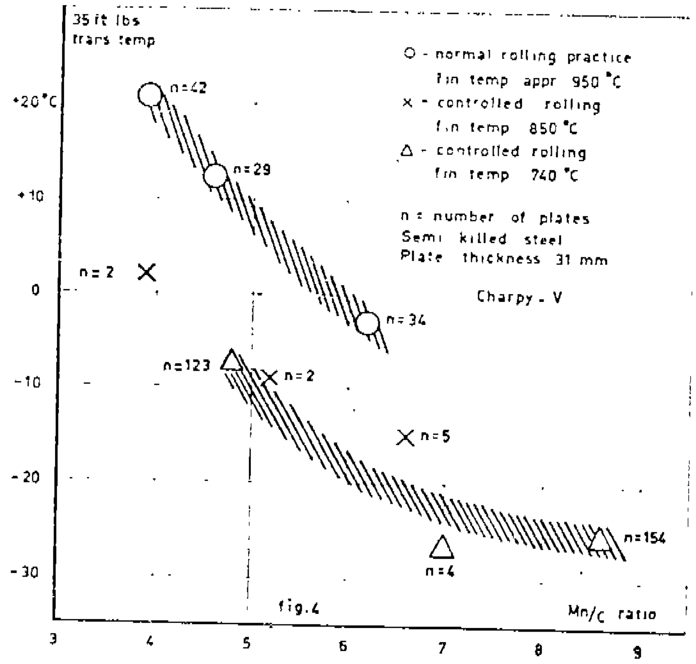

35 ft lbs
trans temp
+20°C
+10
0
-10
-20
-30
3
4
5
6
7
8
9
Mn/C ratio
n=42
n=29
n=34
n=2
n=123
n=2
n=5
n=4
n=154
○ - normal rolling practice fin temp appr 950 °C
× - controlled rolling fin temp 850 °C
Δ - controlled rolling fin temp 740 °C
n = number of plates
Semi killed steel
Plate thickness 31 mm
Charpy - V

fig.4

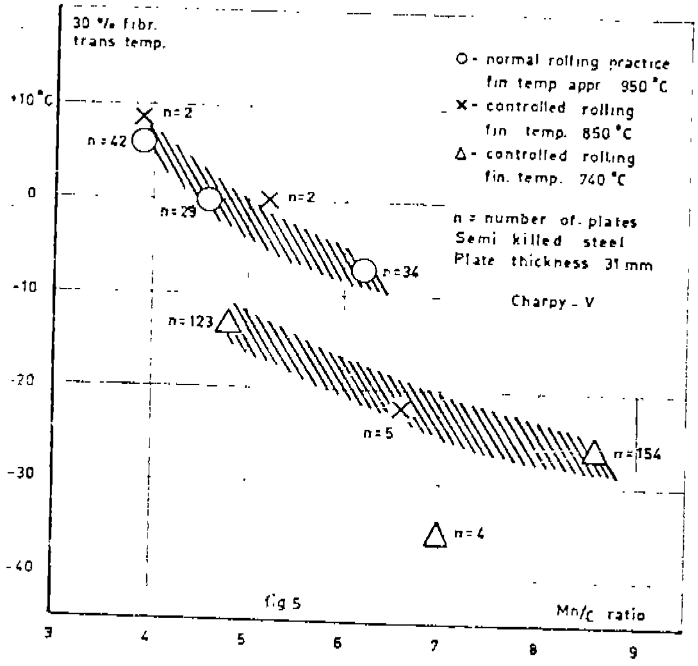

30 % fibr.
trans temp.
+10°C
0
-10
-20
-30
-40
3
4
5
6
7
8
9
Mn/C ratio
n=2
n=42
n=29
n=2
n=34
n=123
n=5
n=154
n=4
○ - normal rolling practice fin temp appr 950 °C
× - controlled rolling fin temp. 850 °C
Δ - controlled rolling fin. temp. 740 °C
n = number of plates
Semi killed steel
Plate thickness 31 mm
Charpy - V

fig 5

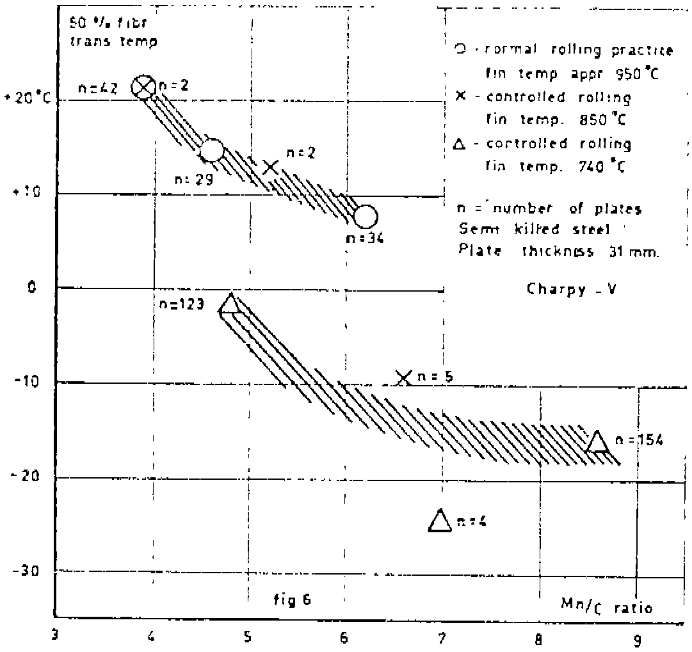

50 % fibr trans temp
+20 °C
+10
0
-10
-20
-30
n=42
n=2
n=29
n=2
n=34
n=123
n=5
n=154
n=4
○ - normal rolling practice fin temp appr 950 °C
× - controlled rolling fin. temp. 850 °C
△ - controlled rolling fin. temp. 740 °C
n = number of plates
Semi killed steel
Plate thickness 31 mm.
Charpy - V
Mn/C ratio
3
4
5
6
7
8
9

fig 6

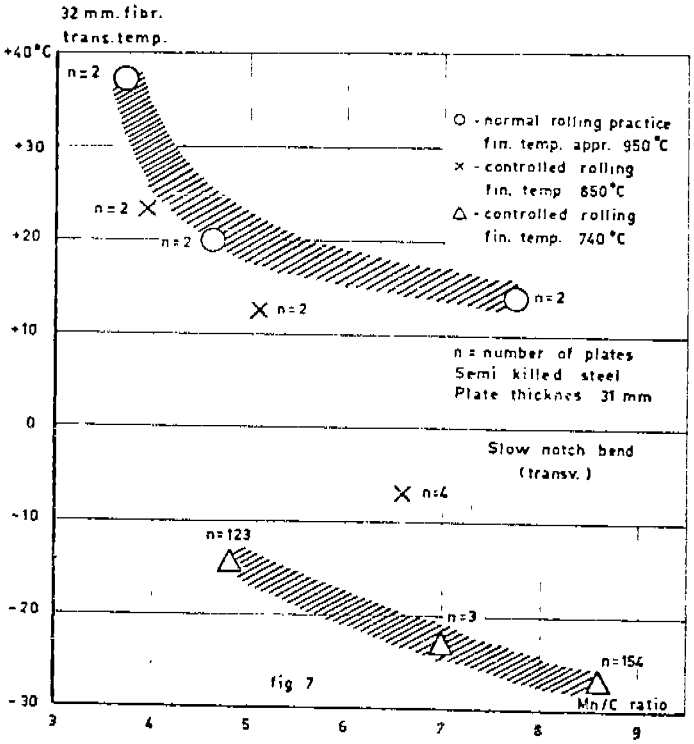

32 mm. fibr. trans. temp.
+40 °C
+30
+20
+10
0
-10
-20
-30
n=2
n=2
n=2
n=2
n=2
n=4
n=123
n=3
n=154
○ - normal rolling practice fin. temp. appr. 950 °C
× - controlled rolling fin. temp 850 °C
△ - controlled rolling fin. temp. 740 °C
n = number of plates
Semi killed steel
Plate thicknes 31 mm
Slow notch bend (transv.)
Mn/C ratio
3
4
5
6
7
8
9

fig 7

The following conclusions might be drawn:

-For semikilled steel, normally rolled, an increase of the Mn/C ratio causes improvements of the energy-transition temperatures in the Charpy V-notch test (15 ft-lb and 35 ft-lb), which are larger than the improvements of the fracture-appearance-transition temperatures (30% and 50% fibrous). Thus, high manganese, apart from shifting the energy-versus-temperature curve to lower temperatures, appears to raise the maximum level of this curve, and raises the energy level at 50% fibrous.

-For semikilled steel, controlled rolled, the difference between energy-and fracture-appearance-transition temperatures in the Charpy test, with regard to their susceptibility to increased Mn/C ratio, appears to be smaller than for normally rolled steel.

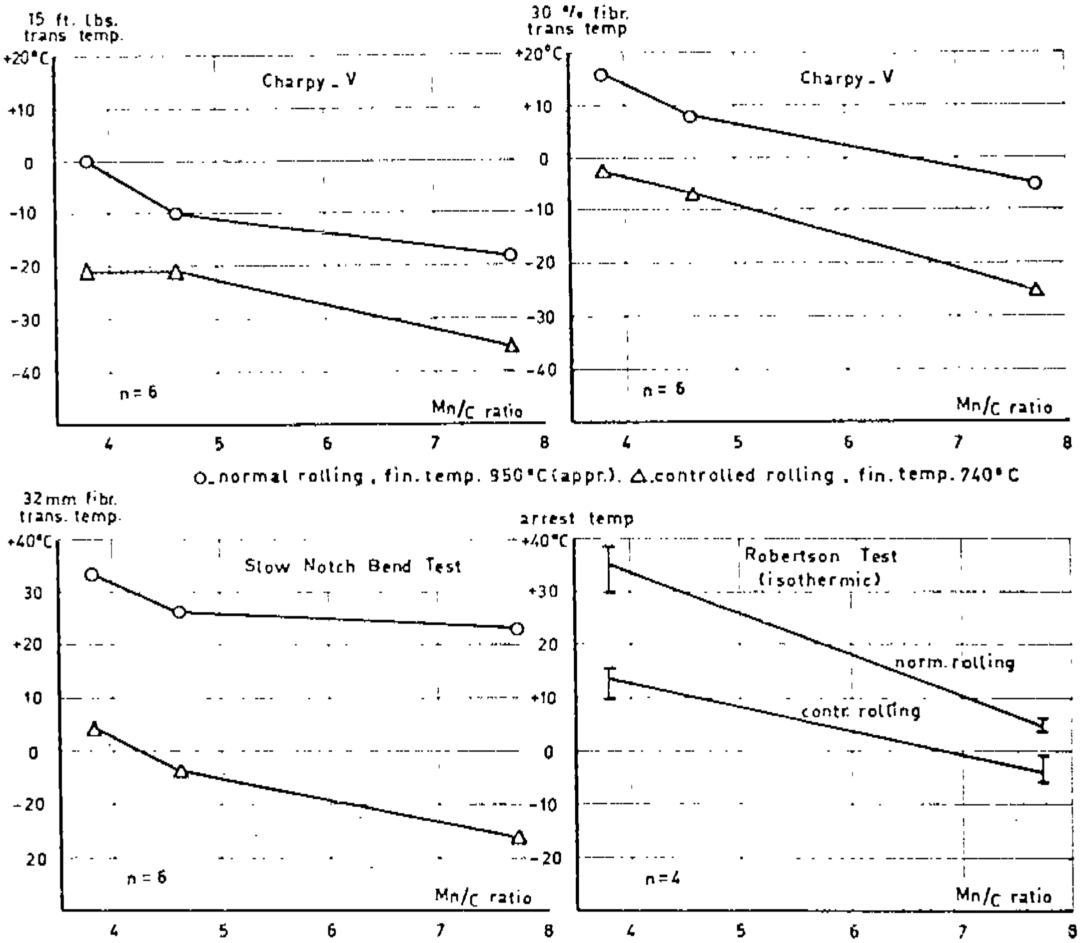
-For semikilled steel, controlled rolling appears to have a larger effect on the 35 ft-lb and the 50% fibrous-transition temperatures in the Charpy V-notch test than on the 15 ft-lb and the 30% fibrous-transition temperatures. Thus, controlled rolling, apart from shifting the energy-versus-temperature curve to lower temperatures, appears to increase the slope of this curve.

-The effect of controlled rolling on the fracture-transition temperature in the slow notch-bend test is almost twice as large as the effect on Charpy V-notch-transition temperatures.

The difference between the effect of high Mn/C ratio and controlled rolling on test results is probably due to a different influence of these factors on the microstructure of the finished plate. Controlled rolling is known to affect mainly the grain size. With regard to the effect of a high Mn/C ratio on microstructure, no common knowledge seems to exist. The amount of pearlite, the spacing of cementite lamellae, and the strength of the ferrite may be affected, partly owing to changes in transformation characteristics.

ROBERTSON TESTS AT DIFFERENT LEVELS OF Mn/C RATIO AND FINISH-ROLLING TEMPERATURE

The effects of thickness, Mn and controlled rolling, discussed in the preceding paragraphs are confirmed, at least qualitatively, by the test results obtained from the 12 Dutch plates (semikilled steel) that were sent to the Committee on Ship Steel for further investigation. In this program, two thickness levels (3/4 and 1 1/2 in.), three levels of Mn/C ratio and two methods of rolling (high finishing and controlled rolling) were chosen. Charpy V-notch and slow notch-bend test results, obtained in our laboratory, were reported to the Committee in December 1957. Since then, Robertson tests have been made on samples from some of these plates by Professor Soete's laboratory at Ghent University. In the first series of tests a temperature gradient was maintained in the test piece, according to Robertson's method, in order to determine the arrest temperature, defined by the first appearance of shear lips at the edges of the fracture. It proved difficult to determine, with sufficient accuracy, the point at which shear lips started. Doubt arose as to whether the appearance of a shear lip was the right criterion. The shape of the brittle parabola, beyond the point at which the shear lips started, was found to be different for different rolling methods. For high finished steels the parabola was much longer and sharper, i.e., it extended much farther into the region of higher temperatures, than for controlled-rolled steels. Further, the appearance of the fracture surface was different: high-finished steel showed a coarse surface with chevron pattern, controlled-rolled steel a much smoother and finer-grained surface. Moreover it was found, in tests with a uniform temperature in the propagation part of the specimen, that brittle fractures could be accompanied by shear lips without being arrested in the test piece (length 12 in.). After this experience it was decided to estimate the arrest temperatures by means of a limited series of isothermic tests (about 4 or 5) from each plate. In these tests the larger part of the specimen (beyond the initiation zone) was kept at a uniform temperature. After doing a small series of tests at different temperatures, an arrest temperature was estimated: above this temperature brittle fracture was arrested, below this temperature the whole test piece



6 plates (38 mm) of semi-killed steel from the Royal Dutch Steelworks sent to the National Academy of Sciences (S.S.C.) in December 1957

fig. 8

broke in a brittle manner. The arrest temperatures, found by this method for 4 of the 12 plates (thickness 1 1/2 in.) are represented in Fig. 8, together with some of the test results of Charpy V-notch and slow notch-bend tests. In a qualitative way the Robertson results are similar to the results in the other tests. The influence of controlled rolling, however, appears to be related to the Mn/C ratio and vice-versa.

It should be noted that the arrest temperatures found by isothermic tests were considerably higher (sometimes 20 C) than the arrest temperatures esti-

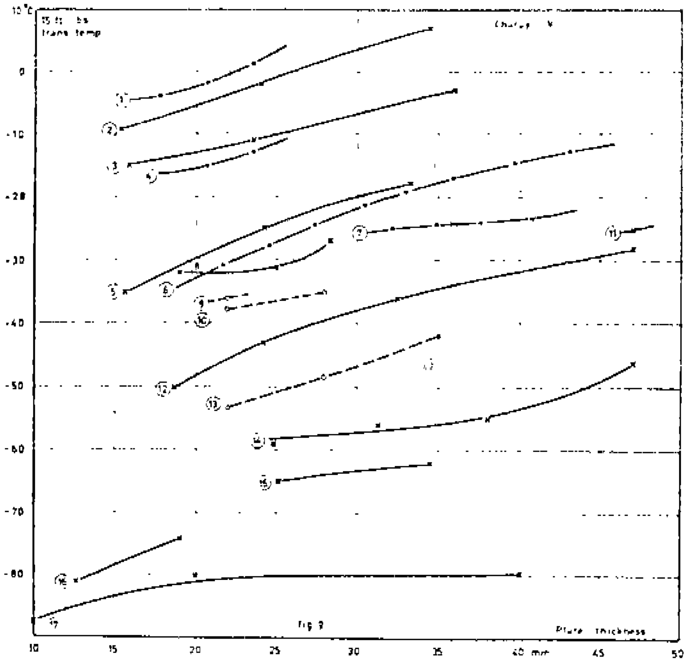

10 °C
15 ft lbs
trans temp
Charpy V
0
-10
-20
-30
-40
-50
-60
-70
-80
①
②
③
④
⑤
⑥
⑦
⑧
⑨
⑩
⑪
⑫
⑬
⑭
⑮
⑯
17
Plate thickness
10
15
20
25
30
35
40 mm
45
50

fig 9

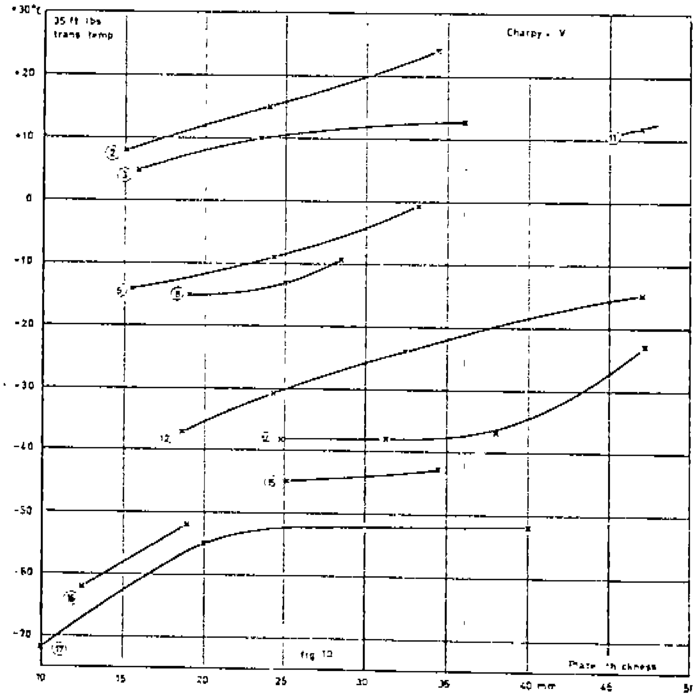

+30 °C
35 ft lbs
trans temp
Charpy - V
+20
+10
0
-10
-20
-30
-40
-50
-60
-70
②
③
⑪
5
⑧
12
14
⑮
⑯
⑰
Plate thickness
10
15
20
25
30
35
40 mm
45
50

fig 10

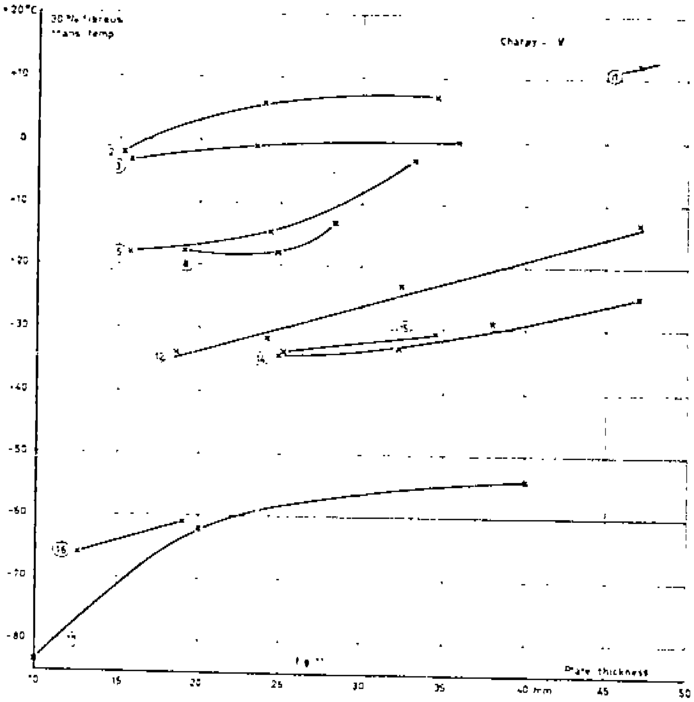

+20°C
30 % fibrous
trans. temp.
Charpy - V
+10
0
-10
-20
-30
-40
-50
-60
-70
-80
2
3
5
8
11
12
14
15
16
17
Plate thickness
10
15
20
25
30
35
40 mm
45
50

Fig 11

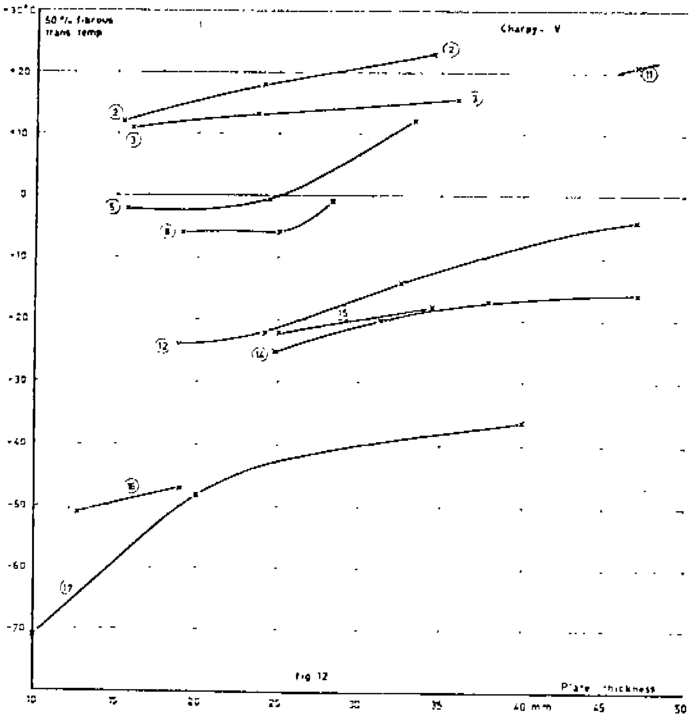

+30°C
50 % fibrous
trans. temp.
Charpy - V
+20
+10
0
-10
-20
-30
-40
-50
-60
-70
2
3
5
8
11
12
14
15
16
17
Plate thickness
10
15
20
25
30
35
40 mm
45
50

fig 12

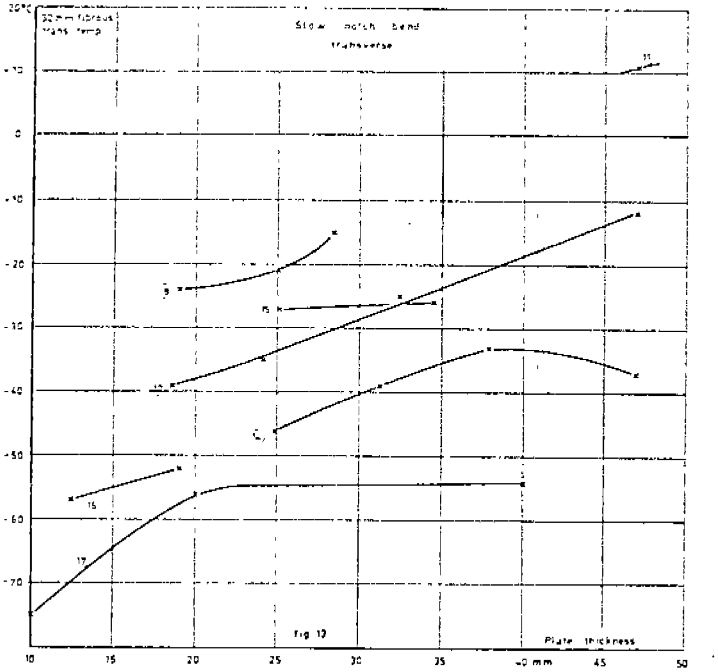


Fig 13

mated by the shear-lip method in tests with a temperature gradient.

SUMMARY OF METALLURGICAL FACTORS

A summary of the effects of various metallurgical factors on test results is given in Figs. 9--13. Particulars of the steels concerned are given in Table 3. The effects of deoxidation practice (Si-Al killed versus semikilled) and normalizing, which were not discussed in the preceding paragraphs, may be derived from the summarizing figures. No data were available on normalized semikilled steel.

Figures 9 to 13 are extensions of Fig. 1 in Vanderbeck's paper "Controlled Low-Temperature Hot Rolling as Practiced in Europe" (Welding Journal, March 1958). The data on American and Belgian steels were reproduced from Vanderbeck's paper (only 15 ft-lb transition temperature in the Charpy V-notch test). The data on semikilled steels, discussed in the preceding paragraphs, and killed steels of our own production have been added.

Figures 9 to 13 permit a check of the conclusions drawn in the preceding

TABLE 3

PROCESSING, CHEMICAL COMPOSITIONS, AND VARIOUS TRANSITION TEMPERATURE EVALUATIONS OF SEVENTEEN STEELS PLOTTED IN FIG. 9-13

Steel	Classification	Processing	Number of plates	thickness range, mm low	avg.	high	C% range low	avg.	high	Mn % range low	avg.	high	Si % range low	avg.	high	Avg. Mn/C Ratio	Charpy-V transition temperatures 15 ft-lb energy	35 ft-lb energy	30% fibrous	50% fibrous	Slow Notch Bend Test
(1)	U.S.A. Data, old class B	Semikilled, normal rolling						.18			.70					3.9					
(2)	Holland, LR - P 402	Semikilled, normal rolling	19	14	15.3	17.5	.15	.166	.18	.64	.671	.70	.03	.04	.05		- 9	8	-2	12	
			17	22	24.1	28	.15	.17	.18	.60	.67	.70	.03	.04	.05	3.9	- 2	15	6	18	
			6	32	34.5	38	.15	.173	.19	.62	.66	.70	.07	.04	.05		7	24	7	23	
(3)	Holland, LR - P 402	Semikilled, normal rolling	15	14	15.8	19	.13	.163	.18	.75	.79	.84	.03	.04	.05		-15	5	- 3	11	
			11	22	23.6	27.5	.16	.19	.20	.75	.79	.84	.03	.04	.05	4.6	-11	10	- 1	13	
			3	35	36	38	.17	.178	.19	.76	.76	.76	.03	.04	.05		- 3	13	0	16	
(4)	U.S.A. Data, new ABS B	Semikilled, normal rolling						.16			.90					5.6					
(5)	Holland, LR - P 402	Semikilled, normal rolling	20	14	15.6	19	.14	.156	.19	.89	.985	1.15	.03	.04	.05	6.2	-35	-14	-18	- 2	
			11	22	24.3	28	.14	.152	.17	.80	1.00	1.08	.02	.03	.04		-25	- 9	-15	1	
			3	32	33.3	35	.14	.153	.16	.67	.95	1.08	.03	.04	.04		-18	- 1	- 3	12	
(6)	U.S.A. Data	Semikilled, normal rolling						.16			1.25					7.8					
(7)	U.S.A. Data, ABS Class C	Si-Al killed, normal rolling						.18			.70			.22		3.9					
(8)	Holland, LR - P 403	Semikilled, controlled rolling	39		19												-32	-15	-17	- 6	-24
			41		25		.15	.17	.20	.71	.81	.95	.03	.047	.06	4.8	-31	-13	-18	- 6	-21
			43		28.4												-27	- 9	-13	- 1	-15
(9)	Belgium, Cockerill-Ougrée	Semikilled, controlled rolling	185					.14			.85					6.1					
(10)	Belgium, Cockerill-Ougrée	Si-Al killed, normal rolling, as rolled	152					.15			.94			.18		6.3					
(11)	Holland	Si-Al killed, normal rolling as rolled	5		47			.155			.94			.08		6.1	-25	12	12	21	11
(12)	Holland, LR - P 403	Semikilled, controlled rolling high manganese	46		18.6												-50	-37	-34	-24	-39
			48		24.2		.11	.13	.16	.90	1.12	1.33	.03	.042	.06	8.6	-43	-31	-32	-22	-31
			49		32.5												-36	-24	-21	-11	-25
			11		47.0		.105	.115	.125	1.01	1.05	1.09	.04	.04	.05		-27	-15	-13	- 4	-12
(13)	Belgium, Cockerill-Ougrée	Si-Al killed, controlled rolling	388					.13			.97			.21		7.5					
(14)	Holland, LR - XNT 2 low silicon	Si-Al killed, normal rolling normalized	27	20.5	24.8	27.5											-59	-38	-34	-25	-40
			19	28	31.3	33	.14	.17	.19	.73	.86	1.04	.05	.07	.09	5.1	-56	-38	-13	-20	-39
			22	34	37.9	47											-56	-17	-29	-17	-33
			5		47			.155			.94			.08			-46	-23	-25	-16	-37
(15)	Holland, LR - XNT 1 high silicon	Si-Al killed, normal rolling normalized	20	19	25.1	33	.14	.16	.17	.69	.79	.90	.10	.13	.19	4.9	-65	-45	-34	-22	-27
			21	34	34.5	40											-62	-43	-31	-18	-26
(16)	Holland, Special NT	Si-Al killed, cross rolled normalized	3														-81	-62	-66	-51	-57
			2														-74	-52	-61	-47	-52
(17)	Holland, high strength Yield point 40 kg/mm2	Si-Al killed, cross rolled normalized	1		10												-85	-72	-83	-71	-75
			2		20				Low Alloy								-80	-55	-62	-48	-56
			1		40												-80	-52	-54	-36	-54

paragraphs with respect to semikilled steels. Steels (1), (2), (3), (4), (5) and (6) are semikilled steels, normally rolled, with respectively increasing Mn/C ratios. Steels (8), (9) and (12) are controlled-rolled, semikilled steels, again with respectively increasing Mn/C ratios.

Contrary to what would be expected, the influence of plate thickness appears to be the same for high-finished and controlled-rolled plates. (Compare steels (5) and (6) with steel (12).) This might be due to the fact that in our method of controlled rolling the thicker plates are rolled with smaller reduction-percentages per pass than the thinner plates.

Steels (7), (10) and (11) are Si-Al killed steels, normally rolled, not normalized, with different Mn/C ratios. The relative position of these steels in Fig. 9 shows that killed steel, as-rolled, can also be improved by increasing the Mn/C ratio.

Steel (13) is a controlled-rolled, killed steel. Steels (14) and (15) are killed steels, high-finished and then normalized. The position of these steels in Fig. 9 shows that killed steel, as-rolled, can also be improved by controlled rolling, and that killed steel, high-finished and then normalized, has better properties than controlled-rolled killed steel, in the as-rolled condition.

Steels (16) and (17) are normalized, killed steels for special applications. Recent experiments with steel (17) have shown that the notch toughness of this steel can still be further improved.

The main conclusions that can be drawn from Figs. 9 to 13, are related to a comparison between killed and semikilled steels. With regard to the 15 ft-lb transition temperature in the Charpy V-notch test (see Fig. 9), the following statements can be made:

-In the as-rolled condition, Si-Al killed steel is better than semikilled steel, if the Mn/C ratios and the rolling methods are the same for both types of steel. (Compare steels (1) and (2) with steel (7), steel (5) with steels (10) and (11), steel (12) with steel (13).)

-The notch-toughness level of Si-Al killed steel, normally rolled, having a Mn/C ratio of about 4 (see steel (7)), can also be obtained with semikilled steel: either by normal rolling of semikilled steel with a Mn/C ratio greater than 8 (see steel (6)), or by controlled rolling of semikilled steel with a Mn/C ratio of 4.8. (See steel (8).)

-The notch-toughness level of Si-Al killed steel, normally rolled, having a Mn/C ratio of about 6, can be surpassed by semikilled steel, if in the latter case controlled rolling is applied and a Mn/C ratio higher than 8 is chosen. (Compare killed steels (10) and (11) with semikilled steel (12).)

-The two preceding statements imply that the manufacturing process should not be prescribed by the customer in order that the steelmaker can choose the most economical manufacturing process for the required level of notch toughness.

The general superiority of killed steel over semikilled steel is largely diminished when other criteria for notch toughness are considered. This is shown by Figs 10--13.

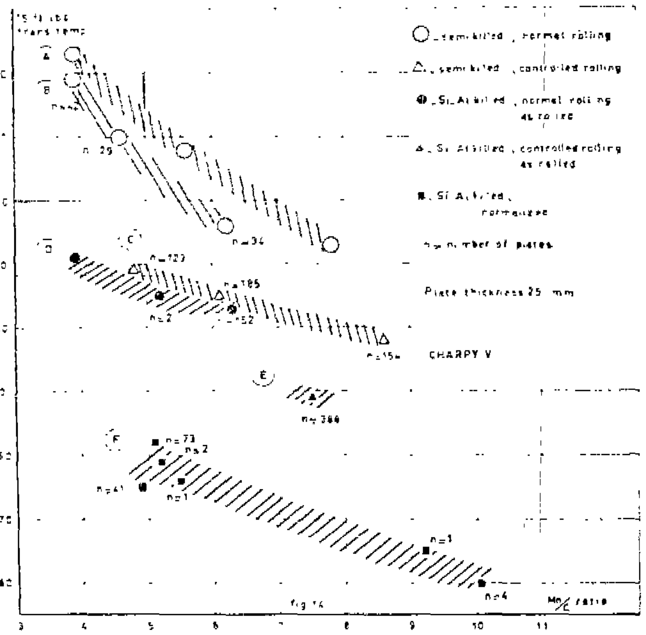
Figure 10 shows the 35 ft-lb transition temperatures of the steels concerned. In this figure, steel (11) (normally rolled, killed steel) is no longer better than steel (5) (semikilled, normally rolled, high Mn), but about equivalent. Moreover, the difference between steel (12) (semikilled, high Mn, controlled-rolled) and steels (14) and (15) (killed, normalized) has become smaller.

This trend is further increased when the 30% and 50% fibrous-transition temperatures are considered (Figs. 11 and 12).

In Fig. 13 (slow notch-bend test) steel (15) is no longer superior to steel (12).

This shift in the position of killed steel, in comparison with semikilled steel, is probably due to a smaller slope of the Charpy energy-versus-temperature curve in the case of killed steel, and to the fact that a certain percentage fibrous corresponds with a higher energy level in the case of killed steel.

It should be noted that the order of merit between steels (14) and (15) is



reversed when fracture-appearance criteria are considered instead of energy criteria. Low-silicon fully killed steel appears to be better than higher-silicon, fully killed steel, when fracture appearance is taken as a criterion.

The fact that the order of merit of the various steels is largely dependent on the criterion chosen, emphasizes the necessity of gaining more knowledge about the correlation between test criteria and service behavior in various applications.

The conclusions derived from Figs. 9--13 are confirmed by Fig. 14--16. These figures were derived from Figs. 9, 11 and 13, and show a cross section of the test results for a thickness of 1 in. Transition temperatures for 1-in. thickness were obtained by interpolation. Some test results, obtained from special investigations, have been added. Details of the steels concerned may be seen in Table 4.

CROSS ROLLING

The rolling process, from ingot to plate, usually consists of two phases: ingot-to-slab and slab-to-plate. In the first phase, the direction of rolling is

TABLE 4

DATA FOR 1-IN. (25 MM) THICK STEEL PLATES PLOTTED IN FIG. 14--16

		% C	% Mn	% Si	Mn/C Ratio	Number of plates	Charpy-V 15 ft-lb	trans. temp. 30% fibrous	S.N.B. test 32-mm fibrous
				Semikilled, normal rolling					
a.	U.S.A. data, old ABS B	.18	.70		3.9		3		
	U.S.A. data, new ABS B	.16	.90		5.6		-12		
	U.S.A. data, high Mn	.16	1.25		7.8		-27		
b.	Holland, LR - P 402	.17	.67		3.9	42	- 1	6	
	Holland, LR - P 402	.17	.78		4.6	29	-10	- 1	
	Holland, LR - P 402	.16$_5$	.99		6.2	34	-24	-14	
	Holland	.19	.74	.04	3.8	2			33
	(6 high finished plates	.19	.90	.04	4.7	2			13
	sent to Ship Structure	.16	.118	.03	7.4	2			6
	Committee in Dec.1957)								
				Semikilled, controlled rolling					
c.	Holland, LR - P 403	.17	.81		4.8	123	-31	-18	-21
	Holland, LR - P 403	.13	1.12		8.6	154	-42	-30	-33
	Belgium, Cockerill-Ougrée	.14	.85		6.1	185	-35		
				Si-Al killed, normal rolling					
d.	U.S.A. data, ABS Class C	.18$_5$	.70	.22$_5$	3.9		-29		
	Holland	.14	.75	.21	5.2	2	-35	-14	- 8
	Belgium, Cockerill-Ougrée	.15	.94	.18	6.3	152	-37		
				Si-Al killed, controlled rolling					
e.	Belgium, Cockerill-Ougree	.13	.97	.21	7.5	388	-51		
				Si-Al killed, normalized					
f.	Holland, XNT, high Si	.16	.79	.13	4.9	41	-65	-34	-27
	Holland, XNT low Si	.17	.86	.07	5.1	73	-58	-34	-46
	Holland	.14	.76	.21	5.4	2	-61	-42	-43
	Holland	.18	.99	.06	5.5	1	-64		
	Holland	.20	1.83	.48	9.2	1	-75		
	Holland	.14	1.47	.26	10.1	4	-80	-58	-55

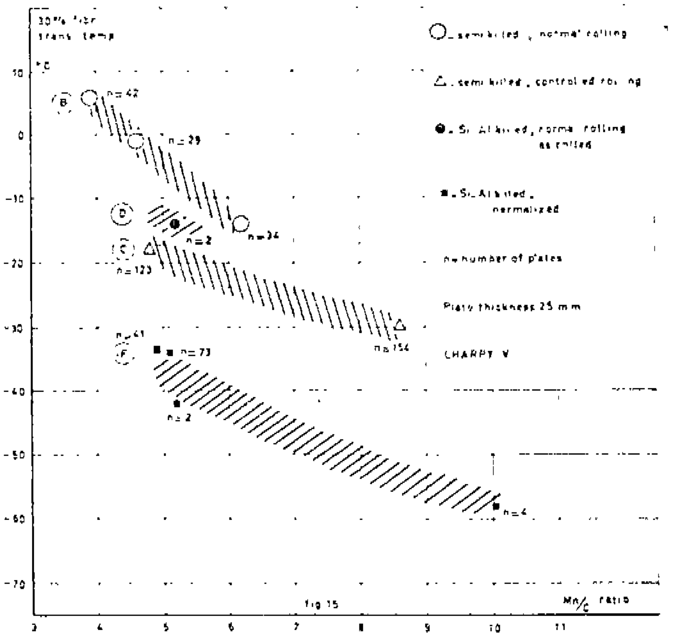

30% fibr trans. temp
°C
10
0
-10
-20
-30
-40
-50
-60
-70
B
D
C
F
n=42
n=29
n=34
n=2
n=123
n=154
n=41
n=73
n=2
n=4
○ _ semi killed , normal rolling
△ _ semi killed , controlled rolling
● _ Si. Al killed , normal rolling as rolled
■ _ Si. Al killed , normalized
n = number of plates
Plate thickness 25 mm
CHARPY V
Mn/C ratio
3
4
5
6
7
8
9
10
11

fig 15

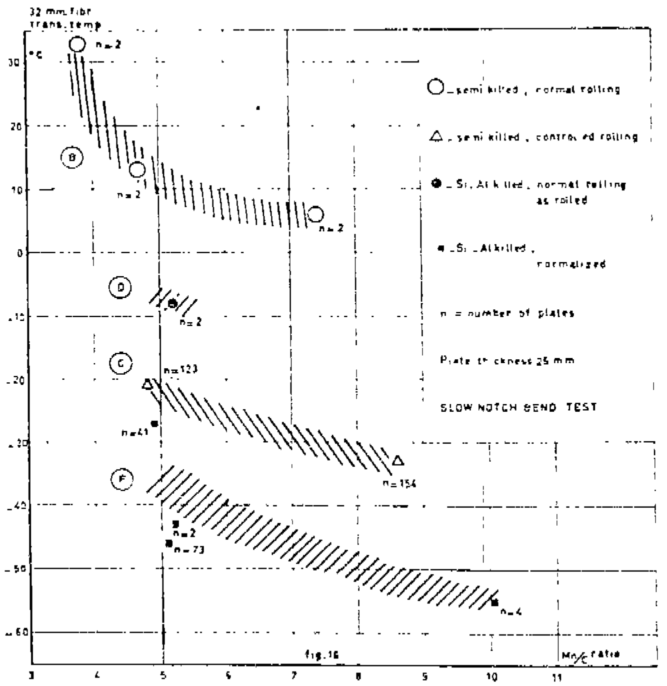

32 mm fibr trans. temp
°C
30
20
10
0
-10
-20
-30
-40
-50
-60
B
D
C
F
n=2
n=2
n=2
n=2
n=123
n=41
n=154
n=2
n=73
n=4
○ _ semi killed , normal rolling
△ _ semi killed , controlled rolling
● _ Si. Al killed , normal rolling as rolled
■ _ Si. _ Al killed , normalized
n = number of plates
Plate thickness 25 mm
SLOW NOTCH BEND TEST
Mn/C ratio
3
4
5
6
7
8
9
10
11

fig. 16

parallel to the vertical axis of the ingot. If the direction of rolling in the second phase is again parallel to the vertical axis of the ingot, the inclusions will be elongated to a large extent, whereas the width of the inclusions will almost not be changed. On the other hand, if the direction of rolling in the second phase is perpendicular to the vertical axis of the ingot (slab rolled cross-wise into plate, length of slab becomes width of plate), the inclusions will be elongated in the first stage of rolling, and widened in the second phase. Their shape will become more like that of discs or pancakes. The shape of the inclusions largely affects the results of notch-toughness tests. When the direction of rolling in the second phase has been parallel to the ingot axis (elongated inclusions) a large difference is found between the test results of longitudinal and transverse Charpy tests. The energy-versus-temperature curve for longitudinal test pieces shows much higher energy levels than the curve for transverse test-pieces. There is a large difference with regard to the maximum energy levels of the curves too. The difference between the curves for fracture appearance as a function of testing temperature is much less spectacular. As a result, the relationships between energy and fracture appearance are entirely different for longitudinal and transverse testing. This offers the interesting possibility to check whether energy or fracture appearance would correlate better with the results of Robertson- and Pellini-drop-weight test results, by doing these tests both parallel and perpendicular to the direction of rolling. It would also be interesting to do explosion bulge tests in order to check whether the extreme directionality in the Charpy-energy test results is confirmed or not.

When the direction of rolling in the second phase is chosen perpendicular to the axis of the ingot, the difference between the test results on longitudinal and transverse tests can be eliminated. This method of rolling improves the transverse test results, whereas the test results in the longitudinal direction become less favorable.

Examples of test results for both ways of rolling are given in Figs. 17--20. These results were obtained from 4 plates, rolled from the same cast. Two plate thicknesses are considered: 1/2 in. and 3/4 in.

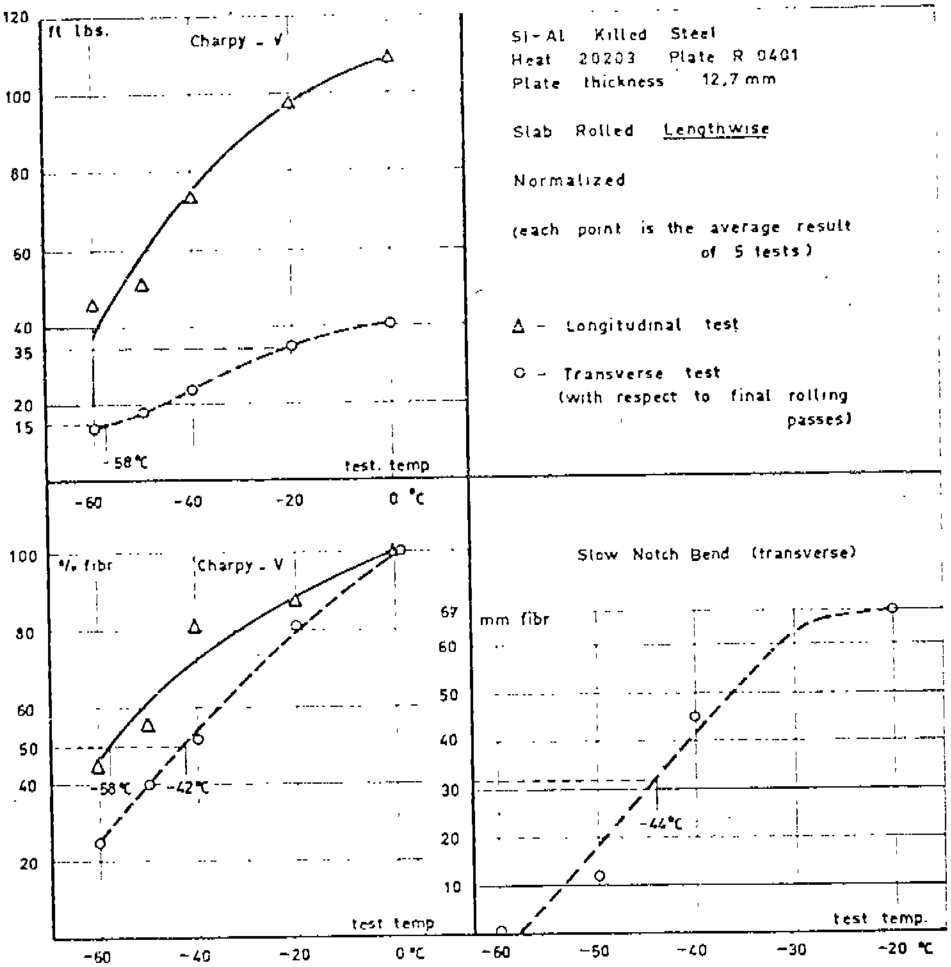


fig. 17

According to the conventional method of testing, i.e., longitudinal tests, the plates that were rolled lengthwise from the slab would make a better impression than the plates that were rolled crosswise from the slab. For some applications, however, we feel that cross rolling should be preferred, in order to obtain equal notch toughness in the two principal directions of the plate.

STRAIN AGING

It is often supposed that Al-killed steel, in the normalized condition, either would not be susceptible to strain aging at all, or less susceptible to

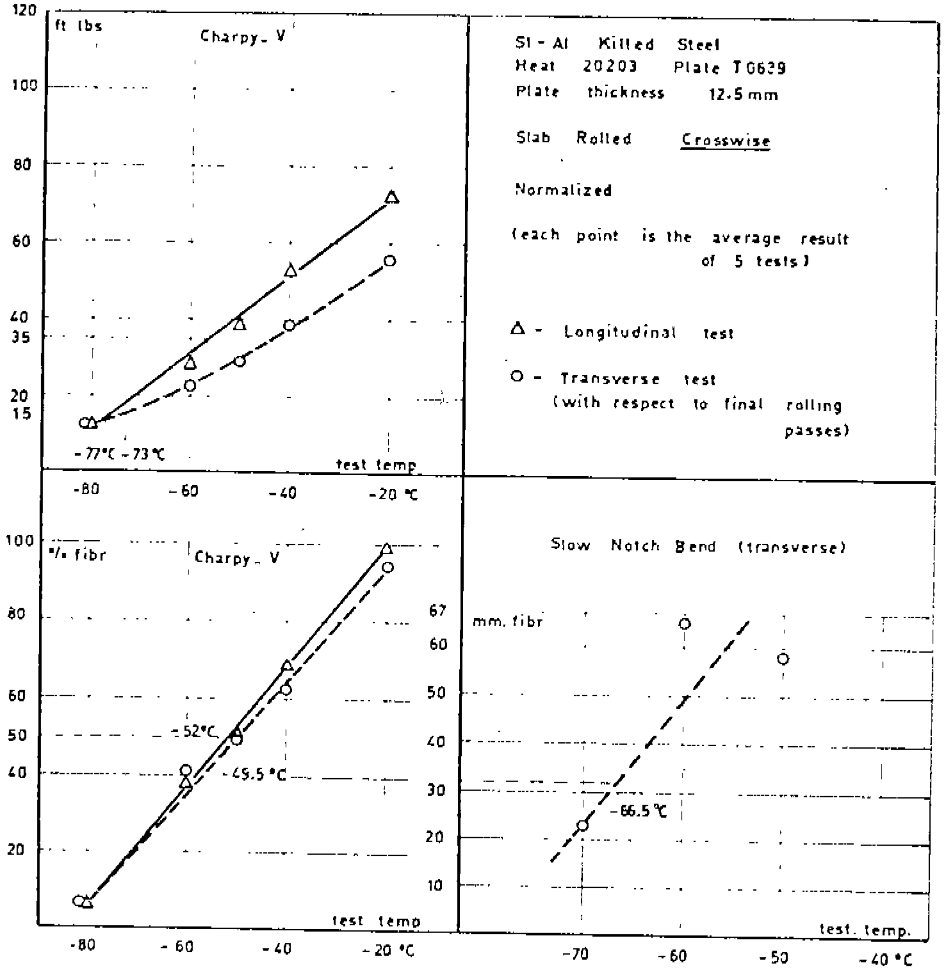


fig. 18

strain aging than semikilled steel. In many instances, this conception leads to the tendency to set up requirements for impact energy before and after artificial aging. In those cases impact tests are required from the steel in the as-received condition, and after the application of 10% strain followed by a heat treatment that consists of keeping the specimen for half an hour at 250 C. The results before and after the aging treatment are compared; sometimes it is required that the impact energy after aging should be at least 60% (for example) of the energy in the as-received condition.

The results of experiments on the influence of artificial strain aging on

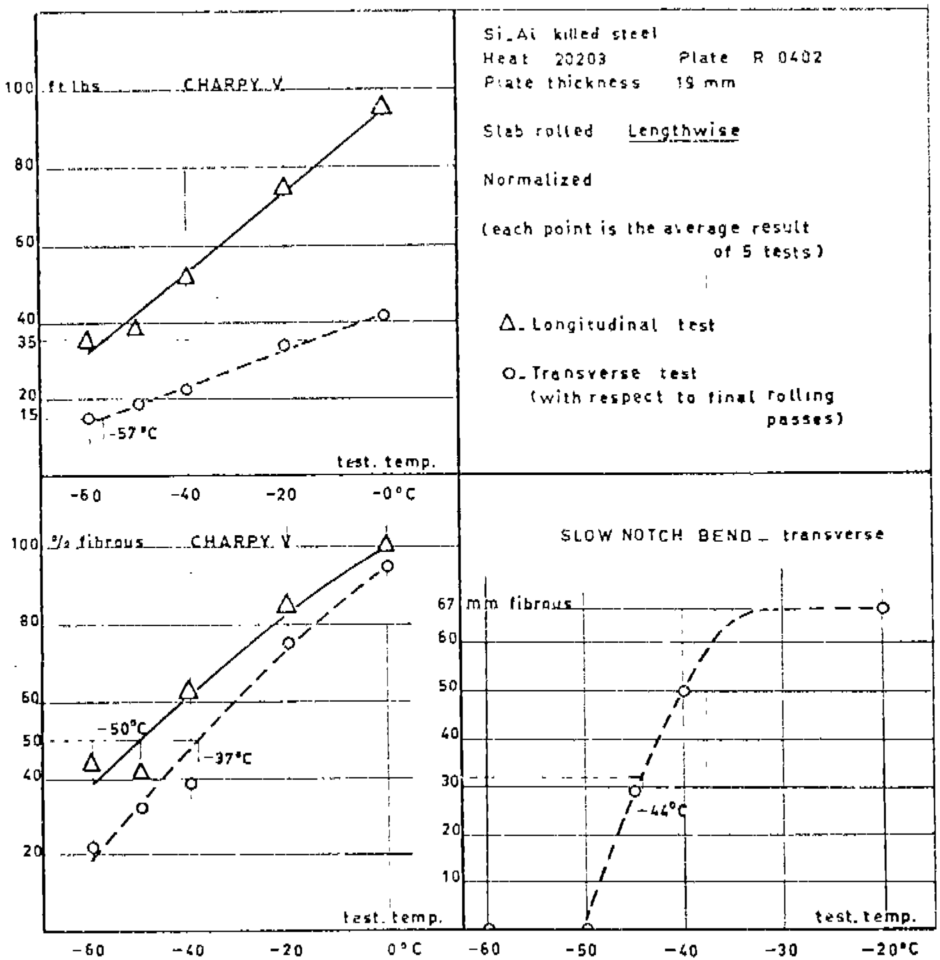


fig.19

Charpy V-notch test results are shown in the Figs. 21 and 22. Semikilled steels, controlled-rolled, are compared with Al-killed steels in the normalized condition.

The results show that the overall influence of strain aging is of the same order of magnitude for both types of steel. This would mean that requirements on impact energy after strain aging could be abandoned and replaced by requirements on impact energy at a lower temperature in the as-received condition.

It should be noted, however, that the separate contributions of strain and heat treatment to the total effect of artificial aging appear to be a little

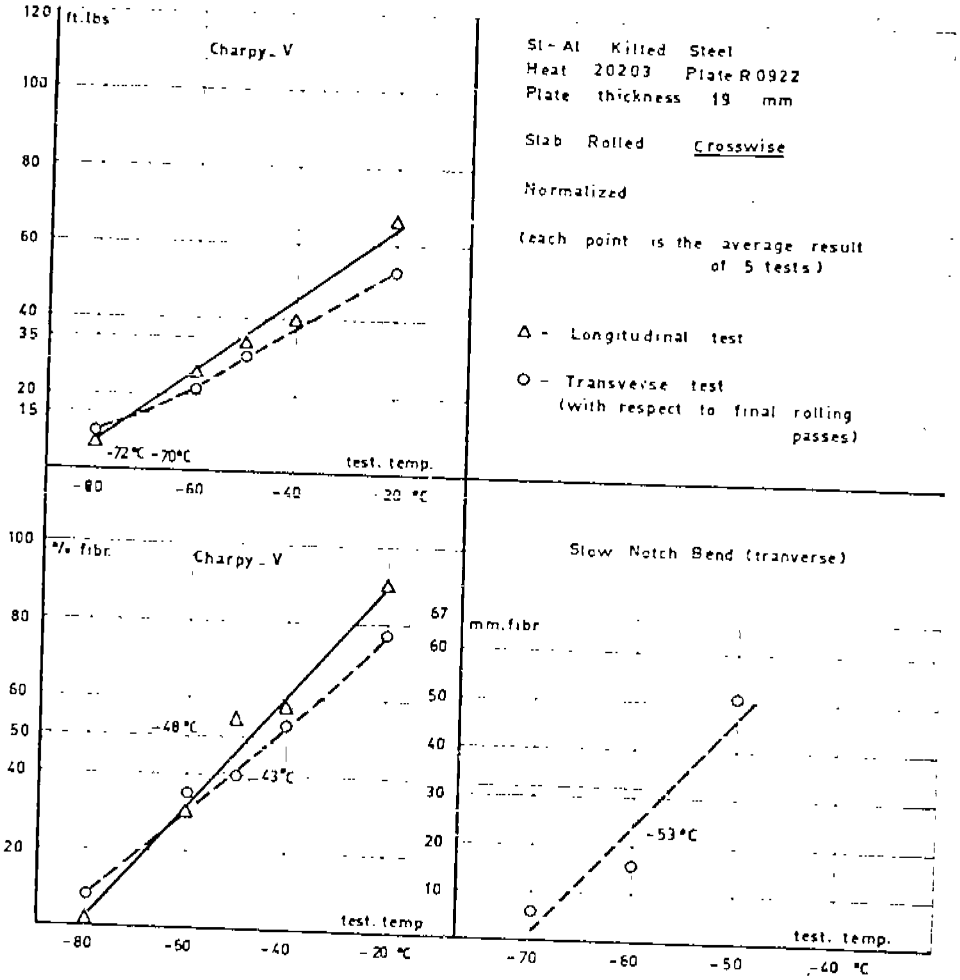


fig. 20

different for the two types of steel considered. The contribution of strain only appears to be larger for killed steel, whereas the contribution of the subsequent heat treatment appears to be larger for semikilled steel.

The absence of substantial difference with regard to aging between semikilled and killed steel is probably explained by the effect of carbon on aging. Though nitrogen will be tied up with aluminum in the case of killed steel, sufficient carbon will be present in both types of steel to cause aging by diffusion of carbon during heat treatment at 250 C.

STRAIN AGEING CHARACTERISTICS OF MILD STEEL
PLATE THICKNESS 30mm
CHARPY V-NOTCH TEST

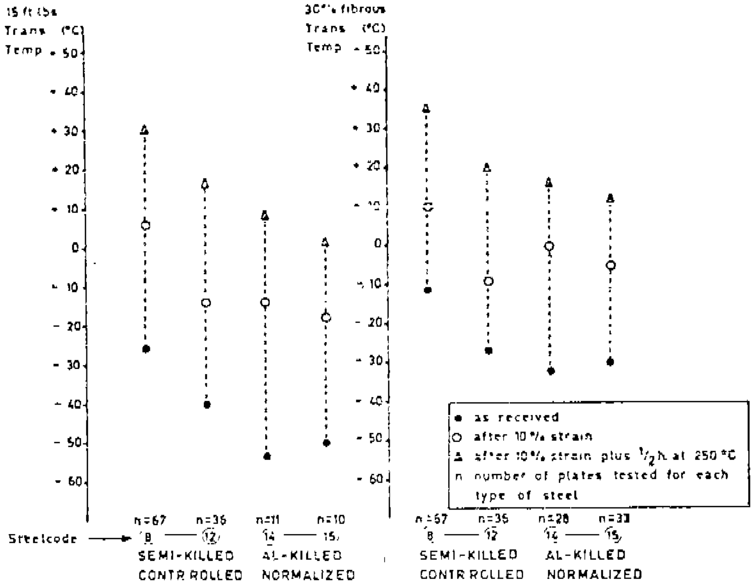


fig 21

STRAIN AGEING CHARACTERISTICS OF MILD STEEL
PLATE THICKNESS 30mm
CHARPY V-NOTCH TEST

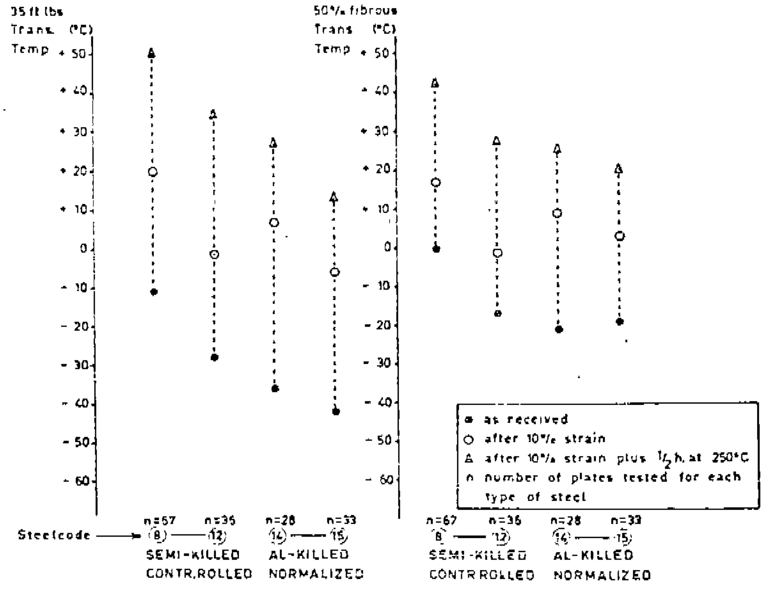


fig 22

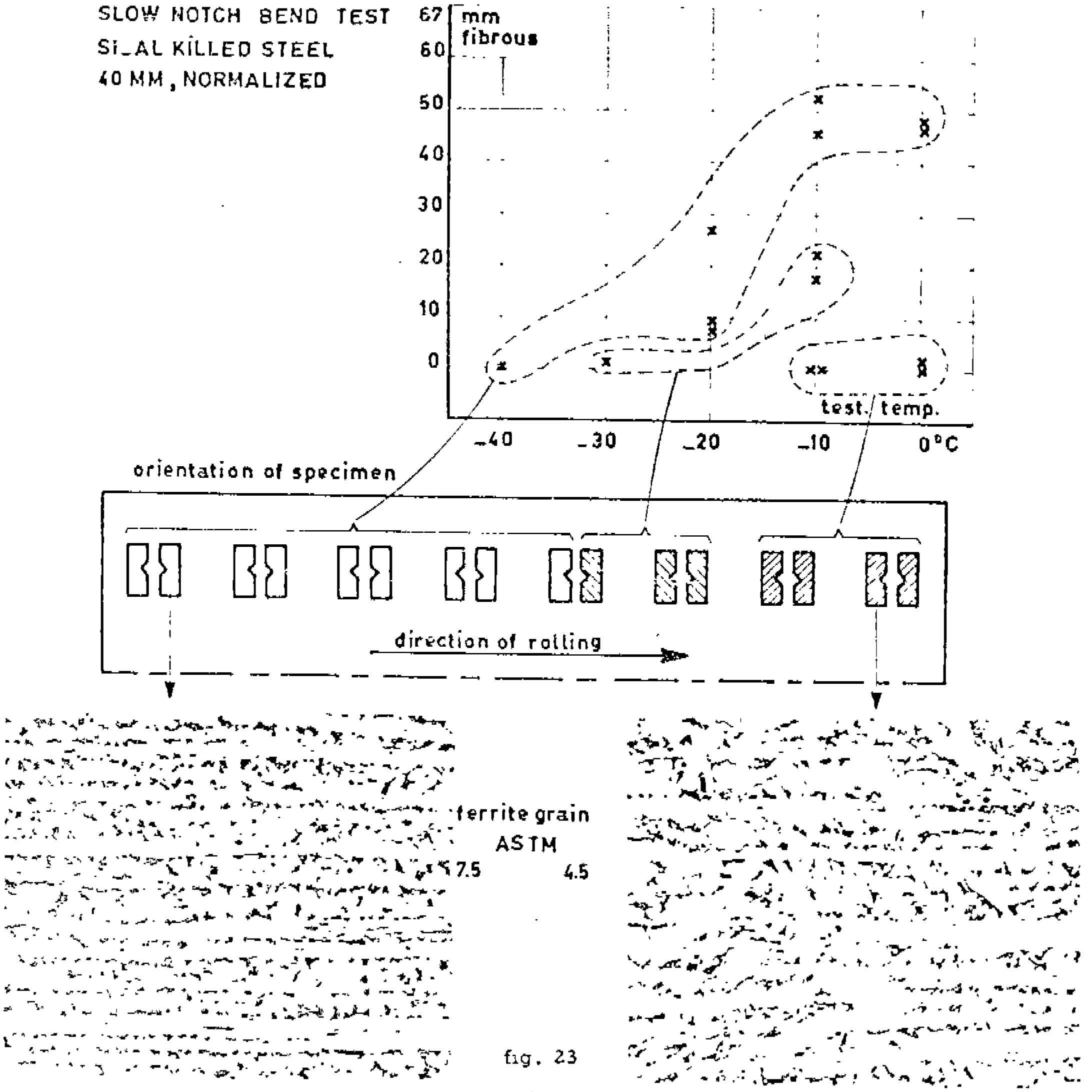


fig. 23

HETEROGENEITY IN PLATES

Heterogeneity in plates may be due to various causes. A typical example of heterogeneity is shown in Fig. 23. This figure refers to a normalized, killed steel plate, having a thickness of 40 mm. Slow notch-bend tests, taken from various locations, did not permit the drawing of a well defined transition curve, because a large scatter of test results occurred. This was considered strange, since in many other cases the slow notch-bend test would give a well

Slow Notch Bend Test. Semi killed steel. Plate A

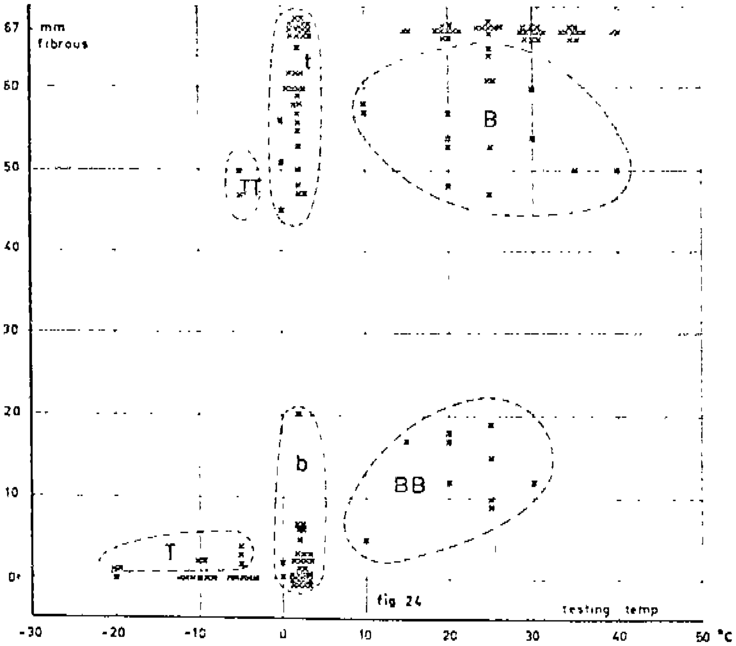


fig 24

Slow Notch Bend Test Semi killed steel Plate A

direction of rolling

t		T	b	t		b	
	t	t		t	B	B	b
t		t			b	BB	BB
t		TT	t		T	b	b
	t			t	B	B	b
		t	t	T	b		BB
t			t	B		b	BB
	t			t	B		b
		t			b		BB
t	T	t	t			b	BB
	t	B		t	b	B	b
TT		t		t	b	B	
b			t			b	b
	t			b	B		b
	T	t	B		b	B	BB
t	t	T	b		B	b	BB
	t	t	B	t	BB	B	b
		t		B	b	b	BB
t			t	T	b		

fig 25

BB = "much too brittle" above the trans. temp   TT = "much too tough" below the trans temp.
B = "too brittle" above the trans temp   T = "too tough" below the trans temp
b = "brittle" at the trans temp   t = "tough" at the trans temp

defined transition temperature. In a further investigation of this case, the slow notch-bend results were divided into three groups. "normally good", "exceptionally bad" and "intermediate" (see Fig. 23). It was found that the test pieces that had shown exceptionally bad results had been taken from a rather narrow band, located along one of the plate edges, perpendicular to the direction of rolling. In this band, a much coarser ferrite grain was found than in the rest of the plate (see Fig. 23). The pearlite structure in this band, however, was not much different from that in the rest of the plate. It was concluded, and this was confirmed by later experiments, that the normalizing temperature in the band must have been too low. This example shows that the simple specification of normalized, killed steel does not guarantee, in all cases, that sufficient notch toughness is attained. If the whole plate had been normalized at a too-low temperature, the whole plate would have had insufficient notch toughness, and yet, formally, it would have been made according to the specification. Therefore, a requirement based on tests taken from the finished product will give a more reliable guarantee.

This example also shows the strong discriminating power of the slow notch-bend test. This is further illustrated by Figs. 24 and 25. Figure 24 shows the slow notch-bend results, obtained from a semikilled steel plate, which (among other plates) was extensively tested in an international (European) investigation of the slow notch-bend test. At first sight the results suggested that the scatter in the slow notch-bend test was so large that the determination of a transition temperature became unreliable. In the further investigation of this case, the slow notch-bend results were divided into different groups, namely (see Fig. 24):

BB = much too brittle above the transition temperature
B = too brittle above the transition temperature
b = brittle at the transition temperature
t = tough at the transition temperature
T = too tough below the transition temperature
TT = much too tough below the transition temperature

Then, the original locations of the test specimens in the plate were traced down, and it was found that the scatter of results could be attributed to heterogeneity of the plate. This is clearly shown by Fig. 25, which needs no further explanation.

APPENDIX I

Influence of high Mn and controlled rolling on the position of semikilled steel in the Boyd diagram.

The different effects of high Mn and controlled rolling on the notch toughness criteria of the Charpy V-notch test can also be illustrated by means of the Boyd diagram. In this diagram percentage fibrous is plotted against impact energy, for a fixed testing temperature (as a rule 0°C).

Figure 26 shows the test results of 4 semikilled steel plates, 3/4 in. in thickness. The figure clearly shows that the position of a steel in this diagram is moved in somewhat different directions, dependent on whether high Mn or controlled rolling is used as a means to improve the steel.

APPENDIX II

Influence of microstructure and chemistry of the plate on notch toughness.

The experience discussed in the preceding part of this paper concerned the relationships between manufacturing variables and various notch toughness criteria. It was realized that the effects of these variables on the mechanical properties would work through changes of chemical analysis and microstructure of the finished product. Attempts have been made, by Mr. H. J Kouwenhoven, of our Laboratory, and Mr. P. Booster, of our Statistical Service, to find correlations between test results, chemistry and microstructure of the plate. The governing characteristics of the plate proved to be the following:

Carbon content (% C)
Manganese content (% Mn)
Phosphorus content (% P)

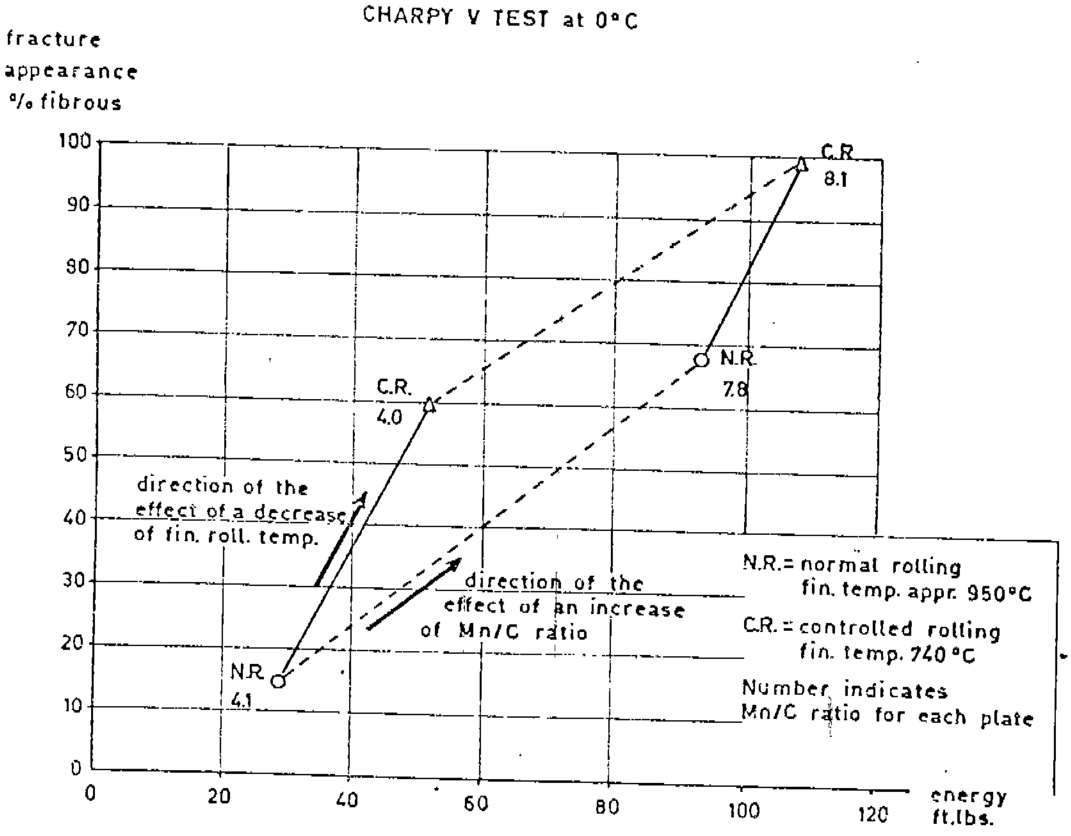


Illustration of the different effects of finishing rolling temperature and Mn/C ratio on the fracture appearance and the impact energy in the Charpy V-notch test (at 0 °C)

4 Plates of semi-killed steel (plate thickness 19mm)

fig. 26

ferrite grain size (ASTM number)

number of inclusions (q)

So far, four formulas have been developed for the calculation of the following four notch-toughness characteristics:

maximum energy level of the Charpy V-notch curve, derived from longitudinal tests;

maximum energy level of the Charpy V-notch curve, derived from transverse tests;

50% fibrous-transition temperature (TT 50), determined from longitudinal Charpy V-notch tests;

32 mm fibrous-transition temperature (TT 32), determined by transverse slow-notch-bend tests;

For the sake of simplicity, only the two last-mentioned formulas will be discussed. These formulas read as follows:

$$\text{TT } 50 = 72 + 210\,(\%\,\text{C}) - 23\,(\%\,\text{Mn}) + 500\,(\%\,\text{P}) - 10.8\,(\text{ASTM No.}) - 0.09\,(q)$$

$$\text{TT } 32 = 93 + 400\,(\%\,\text{C}) - 14\,(\%\,\text{Mn}) + 750\,(\%\,\text{P}) - 16.8\,(\text{ASTM No.}) - 0.28\,(q)$$

The number of inclusions (q) is determined in a plane parallel to the fracture surface, by counting the inclusions longer than 0.02 mm, which are cut by an imaginary line, perpendicular to the plate surfaces, having a length of 100 mm.

The formulas were derived from test results obtained on the following types of steel:

semikilled steel, in the as-rolled condition, made in the open hearth or in the LD-converter:

number of plates : 277
plate thickness : 10 - 40 mm
Carbon content : 0.09 - 0.22%
Manganese content : 0.40 - 1.37%
tensile strength : 37 - 50 kg/mm2

Si-Al killed steel, in the as-rolled condition, made in the open hearth:

number of plates : 33

plate thickness : 10 - 40 mm
Carbon content : 0.08 - 0.22%
Manganese content : 0.33 - 1.34%
tensile strength : 30 - 60 kg/mm2

The standard deviation of the differences between calculated transition temperatures TT 50 and TT 32 and transition temperatures, determined from tests, was found to be 7.5 C and 10.5 C respectively.

The formulas are valid for both semikilled and killed steels, in the as-rolled condition (normal rolling and controlled rolling). This means that TT 50 and TT 32 are the same for killed and semikilled steel, in the as-rolled condition, provided that grain size, Mn, C, P and the number of inclusions are the same in both cases.

On the other hand, normalized killed steel was found to have transition temperatures that were significantly lower than those calculated from the formulas. This would mean that normalizing, apart from refining the grain (which is taken into account by the formula), must have another beneficial effect. Probably this is related to the fact that by normalizing most of the nitrogen, present in the steel, is combined with aluminum and precipitated as aluminum-nitride.

Further, the formulas confirm that the two criteria discussed are affected in a different way by the various characteristics of the plate.

COMMITTEE ON SHIP STEEL
Division of Engineering & Industrial Research
National Academy of Sciences-National Research Council

Chairman:

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

Vice Chairman:

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

Members:

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

Paul Ffield
Assistant Manager of Research
Bethlehem Steel Company

Maxwell Gensamer
Professor of Metallurgy
Columbia University

J. R. Low, Jr.
Head, Metallurgy Research Unit
Research Laboratory, General Electric Company

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

T. T. Watson
Director of Research
Lukens Steel Company