COMPARATIVE COLD-ROLLING TESTS OF OPEN-HEARTH STEEL STRIP (DEEP-DRAWING STOCK) AND ELECTROLYTIC-IRON STRIP

By John R. Freeman, jr., and R. D. France

ABSTRACT

A series of tests has been carried out to determine the relative cold-rolling properties of electrolytic iron as compared with open-hearth steel especially adapted for deep-drawing operations. Representative lots of the two types of material were cold-rolled under identical conditions in order to determine any difference in behavior in the rolls. The material was rolled under both mild and very severe rolling practice. No evidence developed indicating any marked difference between the two types of material.

The following tests were made on samples representing each step in the rolling—hardness, Erichsen, tensile, and bend tests.

These tests showed that electrolytic iron does not harden so rapidly and does not increase in tensile strength so rapidly with cold-rolling as open-hearth steel used for deep-drawing operations. The tensile strength of the cold-rolled material was in all cases greater in the direction transverse to rolling than in the direction parallel to rolling. The hardness was found to approach a maximum with increasing total reductions and then to decrease with further cold-rolling.

In general, the tests indicate that electrolytic iron would probably be slightly superior to specially selected commercial open-hearth deep-drawing stock.

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I. INTRODUCTION

The investigation reported in this paper was undertaken by request of the General Electric Co., who, through their representative, C. A. Hansen, obtained all material and cooperated in the planning and carrying out of all rolling experiments.

The purpose of the investigation was to determine if electrolytic iron was superior to the commercial grades of open-hearth steel strip for cold-rolling. In particular, it was desired to ascertain whether electrolytic iron strip could be given a greater total reduction by cold-rolling before an anneal was required than was the case with commercially available strip steel.

Through the courtesy of Mr. Stanford, president and general manager of the Stanford Steel Products Co., all of the cold-rolling was done at that plant by an expert roller.

II. MATERIAL

Three lots of selected open-hearth steel strip especially adapted for deep-stamping work and two lots of electrolytic iron were rolled. The hot-rolled open-hearth strip was 0.065 by $3\frac{1}{16}$ inch in coils. The two lots of electrolytic iron were obtained in tube form, 0.072 and 0.067 inch wall thickness, respectively. The tubes were slit, cold-rolled to 0.065 inch, and trimmed to $3\frac{1}{16}$ inch width.

All samples were cut to lengths of 24 to 26 inches, sand-blasted, and pickled. They were then annealed at 1,400° F. (760° C.) in the regular factory sheet annealing pots of the General Electric Co., the annealing schedule fitting in precisely with the recommendations of the deep-stamping experts who furnished the sample material.

The chemical composition of the material is given in Table 1:

TABLE 1.—*Composition of material rolled*

Lot number	Carbon	Manganese	Phosphorus	Sulphur
	<i>Per cent</i>	<i>Per cent</i>	<i>Per cent</i>	<i>Per cent</i>
1 (open hearth).....	0.06	0.39	0.012	0.049
2 (open hearth).....	.07	.39	.026	.051
3 (open hearth).....	.14	.48	.007	.035
4 (electrolytic).....	.06	.002	.010	.012
5 (electrolytic).....	.05	.010	.006	.009

III. ROLLING SCHEDULES

A series of rolling schedules was first outlined in which it was intended to cover the range from mild commercial practice to an excessively severe practice which it was believed would result in failure in the rolls of some of the samples being compared. These schedules were based on practices recommended by the cold-rolling mills who furnished the material.

In all the series of rollings a coupon sample 18 inches long was sheared from the strip after each pass. These coupon samples were used for tests described later in this paper.

The rolls used were 10-inch diameter and rotated at 50 to 53 revolutions a minute, giving an approximate surface speed of 160 feet a minute.

1. SERIES 1

The first series of rollings was based on the severest recommended schedule. It was found impossible, however, to carry out this proposed schedule within the intended limits for reductions per pass for thickness of strip below 12 mils (0.012 inch) even with the rolls set up as tight as possible.

The reductions actually obtained in this first series, hereinafter referred to as series 1, are given in Table 2.

TABLE 2.—Series 1

Pass number	Sample number	Lot number				
		1	2	3	4	5
		Thickness in mils				
0.....	0	64	64	65	64	64
1.....	1	36	37	38	35	35
2.....	2	24	26	27	23	24
3.....	3	¹ 15	19	21	18	18
4.....	4	12	15	16	13	13
5.....	5	10	11	13	10	10
6 ²	6	6.5	7.5	8.5	6	6

¹ Lot 1 was used as a set-up sample and was passed through rolls twice at this setting.

² The strips from pass No. 5 were doubled and sent through for the sixth pass.

This first series of rolling did not cause failure by edge cracking in any of the samples nor did it develop any noticeable differences between the samples as observed in the rolls.

It therefore seemed unnecessary to carry out any of the other so-called severe schedules, so a second series of rollings was based upon a mild commercial rolling practice hereinafter referred to as series 2.

2. SERIES 2

In this series of rollings it was planned to obtain a 50 per cent reduction in four roll passes, then to divide the rolled material into two parts. One part was then to be box annealed in city gas atmosphere at about 1,400° F. (760° C.), held at temperature between three and four hours and cooled in the gas atmosphere. Both the annealed and unannealed strip were then to be given at the same time a further total reduction of approximately 50 per cent.

The results of these rolling series are given in Table 3, and are hereinafter referred to as series 2 and 2A, respectively.

TABLE 3.—Series 2 and 2A

SERIES 2

Pass number	Sample number	Lot number				
		1	2	3	4	5
		Thickness in. mils				
0.....	0	64	64	65	64	64
1.....	8	47	48	49	48	46
2.....	9	37	39	39	38	37
3.....	10	32	33	33	32	31
4 ¹	11	32	32	32	28	29
5.....	30	25	25	26	24	23
6.....	31	20	19	20	18	17
7.....	(²)	(³)	(³)	(³)	(³)	(³)
8.....	33	12	13	13	12	12

SERIES 2A (ANNEALED)

0 (4).....	⁴ 12(11)	32	32	32	28	29
5.....	13	22	23	24	23	22
6.....	14	17	18	18	18	19
7.....	(³)	(³)	(³)	(³)	(³)	(³)
8.....	16	13	13	13	12	12

¹ Samples were sheared for annealing after this pass and marked No. 12.² No samples.³ About 15 mils.⁴ Samples sheared from No. 11, series 2, were marked, after anneal, No. 12.

The above two series of rollings brought out no perceptible difference in the rolling properties between the several lots of material.

3. SERIES 3

Since the most severe rolling schedule planned did not injure any of the material or bring out any differences in their rolling characteristics, a third series of rollings was made in which it was attempted to severely edge-crack or otherwise injure the samples by very excessive pass reductions.

The rolls were gradually set up, feeding through the 65-mil stock and feeling about for the breaking point. This finally resulted in setting up the rolls as tightly as possible and then sending the 65-mil stock through.

The results of this series, hereinafter referred to as series 3, are given in Table 4.

TABLE 4.—Series 3

Pass number	Sample number	Lot number			
		1	2	3	4
		Thickness in mils			
0.....	0	64	64	65	64
1.....	40	22	22	19	23
2.....	41	17	15	16	15

This very severe treatment failed to split any of the samples. The rolled surfaces, however, appeared pitted and torn when examined under 50 diameters magnification with a binocular microscope, indicating that the rolls were just on the verge of slipping.

4. RESULTS OF ROLLING TESTS

It was the consensus of opinion of all those who witnessed the rolling experiments that no evidence was developed which indicated any appreciable difference in the rolling characteristics of the open-hearth steel strip and electrolytic iron rolled.

IV. TESTS OF ROLLED STRIP

A series of tests on the material "as rolled" was made to determine if there was any marked difference in the properties of the several lots of material caused by the rolling.

The following tests were made on the coupons sheared from strips after each pass through the rolls: Rockwell hardness tests, micro (baby) Brinell tests, Erichsen cupping tests, tensile tests, and bend tests.

1. METHODS OF TEST

(a) **ROCKWELL HARDNESS.**—Tests were made on several specimens representing the thickest and thinnest material, using a standard Rockwell hardness tester. One hundred kilogram and sixty-kilogram loads were tried with one-sixteenth-inch (1.56 mm), one-eighth-inch (3.13 mm), and 0.0394-inch (10 mm) balls. In all cases the depth of impression was so great that its effect was apparent on the reverse side of the specimen, proving that the hardness values obtained were considerably influenced by the support.

It was therefore concluded that the Rockwell hardness test was not a reliable means for determining differences in hardness of such thin material. Values obtained by using several thickness of the sheet were inconsistent and, therefore, considered unreliable.

(b) **MICRO-BRINELL HARDNESS.**—The Brinell hardness numeral of all specimens was determined with a "Micro-Brinell" hardness testing machine. This machine permits the use of a 6.4 kg or 12.8 kg load instead of the standard 3,000 kg or 500 kg load. A one-sixteenth-inch (1.56 mm) ball was used in all cases and the load was maintained 30 seconds. Two impressions were made on a polished surface of each specimen. The diameters of the impressions were measured with a microscope under a magnification of 100 diameters. The average of the readings for two diameters taken at right angles was used as the diameter for each impression and the average hardness numeral of the two impressions taken as the Brinell hardness of the specimen. In all cases the hardness numeral of the two individual impressions checked very closely.

(c) **ERICHSEN CUPPING TESTS.**—The Erichsen cupping tests were made in a standard Erichsen machine. The direction of the crack, whether longitudinal, transverse, or circular, was noted in all cases. Only one test was made for each condition of rolling because of lack of material.

(d) **TENSILE TESTS.**—Because of lack of material it was possible to make tensile tests only on lots Nos. 2 and 4 which are representative of the open-hearth steel and electrolytic iron, respectively.

The thickness of the specimen was in all cases the thickness of strip from which it was machined. Elongation was measured over a gauge length of 1 inch.

In order to obtain uniform loading over the entire cross section of the tensile test, a new type of fixture suggested to the authors by R. S. Johnson, engineer physicist, of the Bureau of Standards, was used. This is shown in Figure 1. The threaded ends of the holders were screwed into the standard tensile testing fixtures which were hung from spherical seats in the heads of the testing machine. The 1,000-pound range of a Riehle 10,000-pound capacity machine was used. The dimensions of the tensile test specimen used are also given in Figure 1.

FIG. 1.—Fixtures for tensile testing of thin sheet metal

(e) **BEND TESTS.**—Two types of bend tests were made on specimens representative of lots Nos. 1, 2, 4, and 5. In one type¹ the clamps shown in Figure 2 were used. The specimen was first clamped tightly in one jaw and held loosely in the other jaw with the nose faces of the jaw in contact. This jaw was then bent through an angle of 90°, during which the specimen slid slightly in the jaw, permitting the strip to bend easily around the two adjacent nose faces. The second clamp was then tightened and the strip bent through repeated angles of 180° and the number of bends to cause failures recorded.

The maximum number of bends necessary to produce failure for annealed material was eight while only one, or at most two, 180° bends produced failure in severely rolled material. The test was,

¹ This is a slight modification of bend test jaws used by G. F. Comstock. See Bulletin 221, Canned Food Containers, National Canners' Assn. Res. Lab 1923, p. 97.

FIG. 2.—Clamps for bend test (type 1)

FIG. 3.—Apparatus for bend test (type 2) side view

therefore, not sufficiently sensitive to bring out any difference in the two types of material and was therefore discarded.

For the second type of bend test apparatus was used which is similar to apparatus developed at the Bureau of Standards by Capt. S. N. Petrenko, associate mechanical engineer, for testing duralumin sheet. In this test the specimen is caused to bend around a radius equal to fifteen times its thickness while under a unit tensile stress of 4,000 lbs./in.² In the tests here reported all specimens were 0.30 inch wide and of the thickness of the strip from which they were cut. The length of specimen was 3 inches.

Figure 3 shows a side elevation of the bend-test apparatus used. It is evident from the photograph that rolls of different diameters may be placed in the steel frame and held in position by the sliding wedges and thumbscrew. The specimen is hung free from a clamp which rests on the rolls, as may be seen in the photograph. In mounting the specimen for test the rolls are only lightly pressed against the specimen. The operation of the test is quite evident, as shown in Figure 4. The frame, at first in a horizontal position, is turned upward through 90° to a vertical position about the further roll as an axis. It is then brought back to the horizontal position and then turned down to a vertical position about the near roll as an axis and then back to the horizontal. The number of complete cycles to cause failure is noted. The load suspended from the specimen causes it to bend around the roll first 90° in one direction and then 90° in the reverse direction. The specimen is, of course, under combined tension and bending stresses.

2. RESULTS OF TESTS ON THE ROLLED STRIP

(a) **HARDNESS.**—The Rockwell hardness tests were rejected for reasons previously stated.

The results from the micro-Brinell hardness tests on specimens from the rolling series Nos. 1, 2, and 3 are presented in the curves given in Figures 5, 6, and 7, respectively. The hardness values are plotted as ordinates and the per cent reduction in thickness as abscissas, where the per cent reduction in thickness is expressed by the equation

$\frac{T_0 - T_1}{T_0} \times 100 = R$, in which T_0 is the original thickness, T_1 the thickness after passing through the rolls, and R the per cent reduction in thickness.

In all three series of rollings the electrolytic iron did not harden by cold work to the same extent as did the open-hearth steel, and the purest material of both types, lot Nos. 5 and 1, respectively, remained, in general, relatively softer under all conditions.

In series 1 (fig. 5) it is noteworthy that all except lot 3 attained a maximum hardness at approximately 70 per cent total reduction,

and with further reduction the hardness decreased. In lot 3 the hardness attained a maximum value at approximately 65 per cent reduction, but with further reduction there was no apparent change in hardness.

FIG. 5.—Relation of micro-Brinell hardness to per cent reduction in thickness (rolling series No. 1)

This apparently anomalous effect of decrease in hardness after a definite reduction by cold-rolling is an interesting confirmation of work reported by Rawdon and Mutchler as was pointed out in the discussion of their paper by one of the authors.²

The total reductions obtained under the rolling conditions of series 2 and 3 approximate the reduction at which a maximum hardness was obtained in series 1 and so give no evidence of the reversal apparent in the first series, although in series 2 there is an apparent tendency of the curves to approach a maximum, particularly lot No. 5. The maximum hardness obtained appears to be independent of the pass reduction.

² Rawdon and Mutchler, The effect of severe cold-working on the scratch and Brinell hardness, Trans. A. I. M. M. E., 70, p. 343; 1924. Also discussion by J. R. Freeman, jr.

FIG. 4.—Apparatus for type 2 bend test in position for test

The effect of an intermediate anneal upon hardness is very apparent. The hardness in all cases decreases to approximately the same value as previous to cold-rolling. A further reduction in thickness again increases the hardness, but for the same total reduction the hardness of material which received an intermediate anneal is less than when not annealed.

FIG. 6.—Relation of micro-Brinell hardness to per cent reduction in thickness (rolling series No. 2)

(b) ERICHSEN CUPPING TESTS.—The results of Erichsen cupping tests are given in Figures 8, 9, and 10, in which the depth of cup obtained is plotted as ordinates and the per cent reduction in thickness of strip as abscissas.

In comparing the relative cold-drawing properties of the several lots of material it should be borne in mind that the depth of cup obtained in the Erichsen test is a function of the thickness of strip tested, so that direct comparison of the drawing characteristics of the

five lots of material should only be made between tests on strip of equal thickness.

The differences in depth of cup obtained on strip before rolling and after the approximate 80 per cent total reduction in series 1 and 50 per cent in series 2 are indicative of the effect of thickness on the Erichsen value.

The curves show in all three series that, for approximately the same amount of cold work by rolling, the electrolytic iron is slightly but consistently superior to lots 1 and 2 of the open-hearth steel

FIG. 7.—Relation of micro-Brinell hardness to per cent reduction in thickness (rolling series No. 3)

strip, but lot number 3 open-hearth strip has apparently the same qualities as the electrolytic iron.

The values obtained in series 1 on the cold-rolled strip after annealing indicate that the very severe total reductions applied have not injured the material.

The cold-rolled strip always failed by splitting parallel to the direction of rolling. This is undoubtedly due to the greater ductility of the cold-rolled strip in the direction of rolling. In annealed strip the crack at failure was circular. There was no perceptible difference in the type of failure for the two types of material.

(c) TENSILE TESTS.—The results of tensile tests on lots Nos. 2 and 4 rolled under series 1, 2, 2A, and 3 are given in Figures 11, 12, and 13, where ultimate tensile strength is plotted as ordinates against per

FIG. 8.—Relation of depth of cup to per cent reduction in thickness (rolling series No. 1)

cent reduction in thickness as abscissas. In all cases the values connected by solid lines are results of tests taken parallel to the direction of rolling, and points connected by dotted lines are the results of tests transverse to the direction of rolling.

The effect of the cold-rolling is evident. It produced in all cases a very marked increase in tensile strength in both the longitudinal

FIG. 9.—Relation of depth of cup to per cent reduction in thickness (rolling series No. 2)

and transverse direction with increased reductions. In general, the electrolytic iron had consistently lower tensile strength, although this

difference is apparently less marked at the higher percentage reduction ratios. Annealing restored the tensile strength to its original value previous to cold-rolling.

FIG. 10.—Relation of depth of cup to per cent reduction in thickness (rolling series No. 3)

The results of elongation measurements over the rather small gauge length of 1 inch showed no apparent difference between the two types of material in either the longitudinal or transverse tests. In all cases for pass reductions greater than 20 per cent the per cent elongation was less than 10 per cent, and for pass reductions greater

than 35 per cent the elongation was less than 5 per cent. The per cent elongation in the direction transverse to rolling was slightly less than in the direction parallel to rolling.

The greater tensile strength in the transverse direction compared to that in the longitudinal specimens is of interest. In this respect the electrolytic iron and mild steel act similarly to zinc³ and nickel.⁴

FIG. 11.—Relation of tensile strength to per cent reduction in thickness (rolling series No. 1)

(d) BEND TESTS.—The results of the bend test can not be readily plotted in the form of curves, and the results between different materials are only directly comparable for tests on material of the

³ Mathewson, Trewin, and Finkelday, "Some properties and applications of rolled zinc strip and drawn zinc rod," Trans. A. I. M. M. E., September, 1919.

⁴ Browne and Thompson, "The physical properties of nickel." Discussion by Price and Davidson, A. I. M. M. E., 64, 1921; p. 387.

same thickness. Due to the fact that the different lots of material did not reduce to the same thickness for the same roll setting, comparative data on specimens from the same pass number are necessarily approximate.

FIG. 12.—Relation of tensile strength to per cent reduction in thickness (rolling series No. 2)

The test, however, did bring out certain very definite information which may be summarized as follows: There is a very marked superiority in the bending qualities in the specimens taken parallel to the direction of rolling as compared to specimens taken transverse to the direction of rolling, which is probably due to the difference in

ductility. This is true not only for the cold-rolled material but also for the lots of strip in the "as received" annealed condition and annealed after cold-rolling.

The material "as received" withstands from 80 to 100 bending cycles before failure when bent so that the fracture is transverse to direction of rolling, while the same material when bent so that fracture is parallel to direction of rolling will withstand only 40 to 50

FIG. 13.—Relation of tensile strength to per cent reduction in thickness (rolling series No. 3)

cycles of bending. The number of cycles to produce failure decreases rapidly with cold-rolling and approaches 30 to 40 cycles for the severely rolled material when fractured transverse to direction of rolling and approximately 5 cycles when the fracture is parallel to direction of rolling.

There is apparently very little difference in bending qualities between the electrolytic iron and open-hearth steel strip as shown by this type of bend test.

V. SUMMARY

A series of tests was carried out to determine the relative cold-rolling properties of electrolytic iron and open-hearth steel strip especially adapted for deep-drawing operations.

A series of comparative rollings was first made to determine any difference in behavior in the rolls between the two types of material. The material was rolled under both mild cold-rolling mill practice and under conditions which would be classed as a very severe practice.

A series of mechanical tests was then made on specimens of both types of material taken to represent all stages of the rolling tests. These tests included hardness tests; Erichsen cupping tests; tensile tests, both longitudinal and transverse to direction of rolling; and bend tests.

VI. CONCLUSIONS

1. In the rolling tests no evidence developed which indicated any appreciable difference in the character of the two types of material rolled.

2. The mechanical tests showed that electrolytic iron does not harden as rapidly and does not increase in tensile strength as rapidly with cold-rolling as open-hearth steel deep-drawing stock.

3. The tensile strength of cold-rolled strip was found in all cases to be higher in the direction transverse to rolling as compared to the direction parallel to rolling.

4. The micro-Brinell hardness tests indicated that the hardness of electrolytic iron and open-hearth steel deep-drawing stock approaches a maximum value with cold-rolling and then decreases in value with further cold-rolling.

5. In general, the tests indicate that electrolytic iron would probably be a somewhat superior material to commercially obtainable open-hearth deep-drawing stock for deep-drawing operations.

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