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EFFECT OF MODERATE COLD-ROLLING ON THE HARDNESS OF THE SURFACE LAYER OF 0.34-PERCENT-CARBON STEEL PLATES

By Harry K. Herschman

ABSTRACT

The influence of moderate cold-rolling on the surface indentation hardness of 0.34-percent-carbon steel plate initially surface-finished by three different methods was investigated. Variations of the hardness of the surface layers extending to different depths below the surface of the specimens were determined by applying different loads on a Knoop indenter. Indentation hardness tests also were made with the Rockwell Superficial hardness machine. The results obtained with the Knoop indenter showed significantly lower hardness numbers for the superficial layer of the steel after the lighter degrees of rolling, the magnitude of change apparently being influenced by the mode of initial finishing. Hardness decreases were not revealed by tests made with the Rockwell Superficial machine nor in any case in which the penetration of the Knoop indenter exceeded about 0.0003 inch.

CONTENTS

I. INTRODUCTION

In cooperation with the Bureau of Engraving and Printing, the National Bureau of Standards is studying the effect of different surface finishes on the engraving and transferring properties of 0.34-percent-carbon steel plates. A previous paper [1][1] on the initial phase of this study described results of surface indentation hardness tests made with an elongated pyramidal-diamond (Knoop) indenter [2] on specimens having different metallographic structures and finished under different grinding conditions. Exploratory experiments with these specimens indicated that burnishing the surface by cold-rolling was accompanied by a decrease in hardness of the superficial layer. This appears to be in accord with recent work of Goss and Brenner [3], who presented hardness (monotron test) data showing a hardness reversal during continued cold-rolling of 0.74-percent-carbon (sorbitized) steel. However, similar experiments by these investigators with this steel in the pearlitic condition showed only progressive hardening. A behavior similar to that of sorbitic steel, reported by Goss and Brenner, has been found also in copper, by Atkin [4] and others [5, 6]. Thomp-

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[1] Figures in brackets indicate the literature references at the end of this paper.

son [7], who observed no indication of hardness reversals during the progressive cold-rolling of either monocrystalline or polycrystalline copper, briefly summarized a number of suggestions offered by other concurring investigators to account for the apparent anomalous behavior of copper. However, these suggestions apparently did not take into consideration the differences in the properties of the metal immediately adjacent to the surface compared with the metal more remote from the surface as a possible factor influencing hardness tests involving shallow indentations. That such a layer, which possesses distinctive characteristics, exists has been borne out by considerable research since Beilby [8] first postulated the formation of an amorphous layer on metals subjected to polishing and other means of cold-working. Because of the distinctive characteristics of the metal near the surface that has been cold-worked, it is reasonable to assume that the results of the hardness tests will be influenced by the depth of penetration of the indenting tool.

The structure of the surface layer of 18–8 stainless steel has been shown by Wulff [9] to be affected to different degrees by different surface-finishing procedures. This is in accord with the results of Chalmers [10], who found by optical-reflectivity means, significantly different surface-hardness values for annealed copper polished with different abrasives. These results suggest that the initial surface finish of a metal may influence the magnitude of the hardness changes in its surface layer caused by light cold-rolling.

This paper summarizes the results of indentation hardness tests made with the Knoop indenter [2] penetrating to progressively increasing depths beneath the surface of specimens initially finished by different methods and then cold-rolled to different degrees. These results are supplemented by the results of hardness tests made on the same specimens with the Rockwell Superficial hardness tester.

II. MATERIAL

The steel investigated was representative of that used for rotary-press printing plates by the Bureau of Engraving and Printing, with respect to both composition and microstructure. The significant constituents, other than iron, determined by chemical analysis were as follows:

Constituent	Percentage
Carbon	0. 34
Manganese	. 48
Phosphorus	. 04
Sulfur	. 04
Silicon	. 20

These plates are hot-rolled and then annealed, and in this condition the metal at, and in, the immediate vicinity of the surfaces usually is nearly free of carbon. In preparing the plates for engraving and transferring, the decarburized layer is completely removed from the side used for transfer purposes by grinding. However, this precaution is not required in finishing the other side of the plates. The

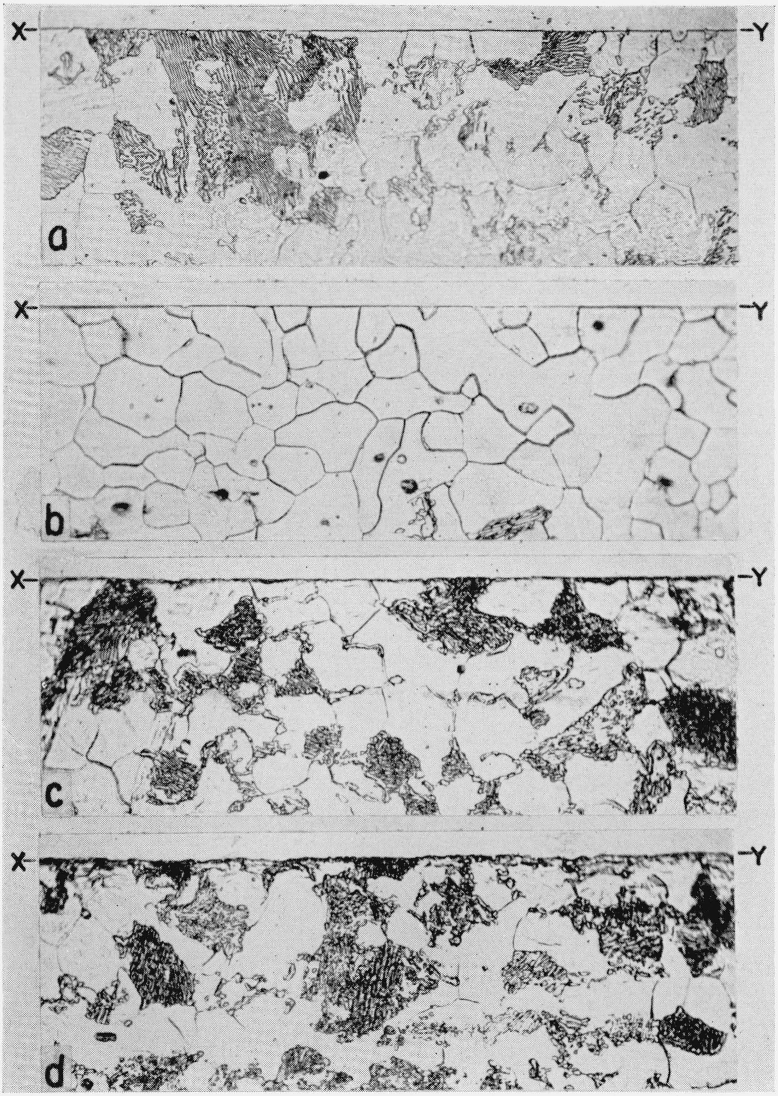

FIGURE 1.—*Characteristic structure of specimens of annealed 0.34-percent-carbon steel as initially surface-finished by different methods, observed in each case in a section perpendicular to the surface under consideration, the trace of which is indicated by line xy.*

a, Surface layer adjacent to transferring surface of plate finished by metallographic polishing. *b*, Decarburized to a depth of 0.01 to 0.02 inch. Surface finished by metallographic polishing. This is characteristic of the surface layer of the underside of transfer intaglio printing plates. *c*, Surface layer adjacent to transferring surface of plate, finished by buffing. *d*, Surface layer adjacent to transferring surface of plate, finished by grinding.

The surfaces (indicated by trace *xy*) of the polished specimens (*a* and *b*) were smooth as compared with those of the specimens buffed and ground, respectively (*c* and *d*). *a*, *c*, and *d* show the microstructural inhomogeneities of the metal adjacent to the test surface (trace *xy*) of the specimens. All the specimens were etched in 1-percent nital. Magnification, ×500.

typical microstructures of the metal near the surface on the two sides of a transfer plate are shown in figure 1 (*a* and *b*, respectively).

The parent test bars used in this study were cut from a single plate of steel to the dimensions 4½ by 1 by ¼ inch thick. Each of these test bars prior to cold-rolling was surface-finished by one of three different methods, as follows:

1. Wet-grinding with a soft alundum abrasive wheel, No. 46 grain, vitrified bond; maximum depth of roughing cuts 0.0005 inch, finishing cut 0.0001 inch.
2. Surface-grinding [2] with a soft wheel and then buffed on a segmented leather "knee" wheel charged with chromic oxide.
3. Wet-grinding as in 1 above, two stages on the tin-lead laps, first with No. 302 abrasive and then with No. 303½ abrasive, and final polishing on velvet charged with a paste of optical rouge in water.

The surface of the plate studied in most cases corresponded to the side of the plate which was free of the decarburized layer. However, metallographic examination frequently has revealed large areas of free ferrite at the transfer surfaces of plates, attributable to various causes. In order to study the effect of rolling on this type of structure, the decarburized side of a series of specimens was polished by method 3, as described above.

III. METHOD OF TEST

1. ROLLING TREATMENTS

All the cold-rolling was done on a two-high rolling mill, power-driven, equipped with hardened steel rolls having a diameter of 5 inches. The specimens were reduced approximately 0.0005 in. in thickness for each pass.

A specimen three-fourths of an inch long was cut from each test bar, as initially surface-finished, and used for hardness tests of the steel in the prerolled condition. The remainder of each bar (about 3¾ by 1 by ¼ inch thick) was cold-rolled to 1-percent reduction in thickness. A coupon approximately 1¼ inch in length was then cut from each bar and reserved for hardness tests. This procedure of rolling and sampling was repeated for nominal reductions of 2 and 4 percent.

2. INDENTATION HARDNESS TESTS

Hardness tests were made with both the Knoop indenter, used with the apparatus described in a previous publication [2], and the Rockwell Superficial hardness tester. The usefulness of the elongated pyramidal-diamond (Knoop) indenter for determining hardness gradients in the surface layer of steel was discussed in the above-mentioned publication [2]. Since preliminary tests suggested that the hardness gradient might be confined to a thin layer immediately below the surface, correspondingly shallow indentations were required to reveal significant changes in hardness in this layer. The smallest load which could be used on the indenter with accuracy, for the apparatus employed, was 50 grams.

Indentation tests with 50-, 100-, 200-, 500-, 1,000-, and 2,000-gram loads on the indenter were made on the finished surface of each speci-

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[2] Representative of the finishing treatment applied by the manufacturer of transfer plate used for the present study.

men. The time of contact of the indenter with the specimen in making a test was 20 seconds. All indentations were made so that the long axis was nearly parallel to the direction of rolling and to the scratch marks on the specimens formed during the initial surface-finishing.

IV. RESULTS AND DISCUSSION

The results of the Knoop indentation tests, determined with different loads on the indenter for each of the specimens before and after rolling, are listed in table 1. These data, graphically presented in figures 2 to 5, show the average hardness changes with each load, which occurred during the progressive stage of rolling. In this manner, the effect of rolling on the hardness of layers differing in thickness can be shown. The curves (*A*, *B*, and *C*, figs. 2 to 5) show in most cases that the hardness numbers determined with the 50-, 100-, and 200-gram loads on the specimens after cold-rolling to 1- and 2-percent reductions were significantly less than they were prior to rolling. However, these same curves in general show a progressive increase

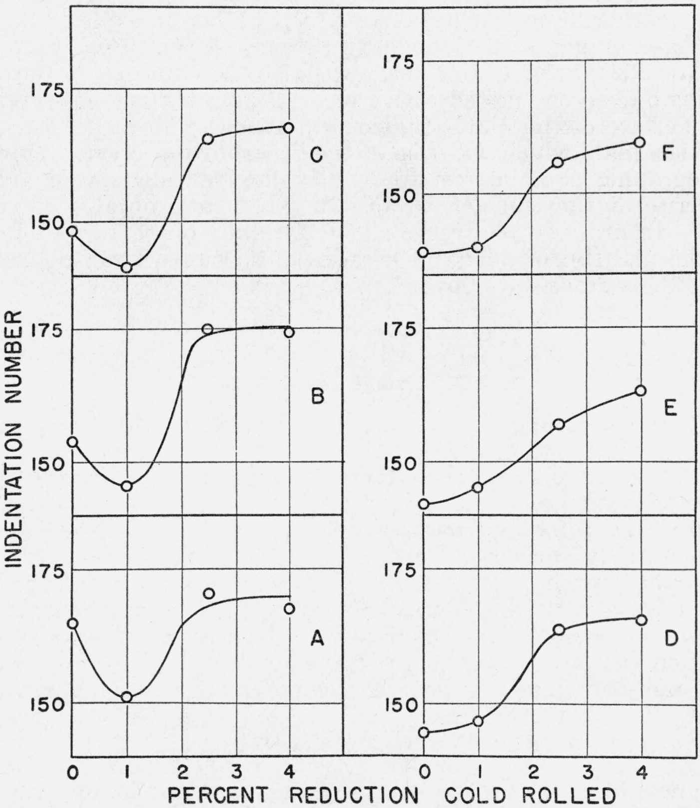

FIGURE 2.—*Influence of cold-rolling on the surface indentation hardness values (Knoop indenter) of annealed 0.34-percent-carbon steel, initially finished by metallographic polishing.*

The loads on the indenter (in grams) for the respective curves were as follows: *A*, 50; *B*, 100; *C*, 200; *D*, 500; *E*, 1,000; *F*, 2,000.

in hardness for reductions greater than 2 percent. This indicates that there was a decrease in hardness during the initial stages of cold-rolling, followed by an increase on further rolling for layers penetrated by the indenter with loads of 50, 100, and 200 grams.

The Knoop hardness numbers obtained with the relatively heavy loads (2,000, 1,000, and in some cases 500 grams, curves *D*, *E*, and *F*, figs. 2 to 5) show no indication of hardness decreases at any of the stages of cold-rolling. These results are in accord with those obtained on the same specimens with the Rockwell Superficial tester (15-kilogram load, ⅟₁₆-inch steel ball; fig. 6). These data indicate that the indentation numbers obtained under these conditions of test were

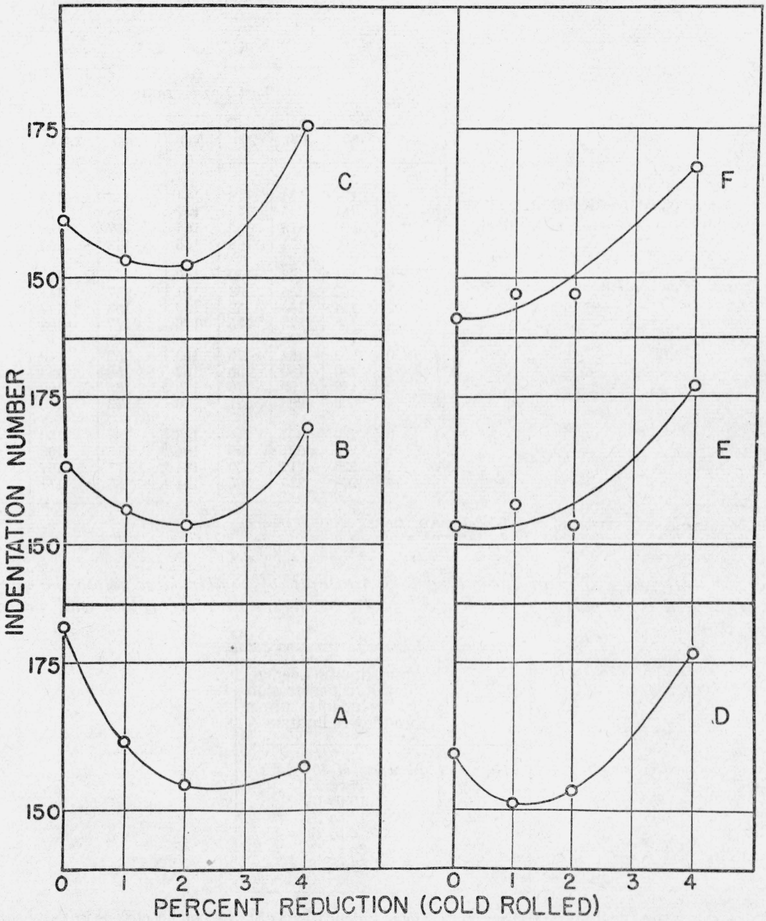

FIGURE 3.—*Influence of cold-rolling on the surface indentation hardness values (Knoop indenter) of annealed 0.34-percent-carbon steel, initially finished by metallographic polishing.*

The test specimens in this case had a decarburized surface layer 0.01 to 0.02 inch in depth.
The loads on the indenter (in grams) for the respective curves were as follows: *A*, 50; *B*, 100; *C*, 200; *D*, 500; *E*, 1,000; *F*, 2,000.

not appreciably influenced by the hardness of the outermost portion of the surface layer (penetrated with the 50-, 100-, and 200-gram loads).

TABLE 1.—*Average indentation hardness (Knoop and Rockwell Superficial) numbers of 0.34-percent-carbon steel specimens (1) as initially surface-finished and (2) after moderate cold-rolling to different degrees*

Initial surface finish	Reduction by cold-rolling	Indentation hardness number						
		Knoop indenter[a]						Rockwell Superficial 15T[b]
		Test Load, grams						
		50	100	200	500	1,000	2,000	
	%							
Metallographic polish (no decarburized layer at surface)	0	164	154	148	144	142	139	83
	1	151	145	142	147	145	140	85
	2. 5	170	175	166	164	157	156	86
	4	168	174	168	166	163	159	87
Metallographic polish (decarburized surface layer)	0	181	163	159	160	153	143	85
	1	162	156	153	151	157	147	85
	2	154	153	152	153	153	147	85
	4	158	170	175	176	177	168	86
Buffed	0	203	183	176	153	152	149	83
	1	180	180	166	162	158	153	85
	2	182	180	176	170	165	160	85
	4	200	200	181	176	173	166	86
Ground	0	230	227	214	188	168	160	83
	1	226	221	209	184	175	163	85
	2	220	212	200	184	177	167	86
	4	228	220	205	191	183	171	87

[a] Each value is the average of 25 to 60 determinations.
[b] Each value is the average of 10 to 15 determinations.

TABLE 2.—*Relationship of indenting load to depth of penetration below the surface of annealed 0.34-percent-carbon steel plate in the moderately rolled and prerolled conditions*

Load	Approximate average depth of penetration of the indenter, upper and lower limits[a]
Grams	*In units of 10^{-5} inch*
50	7 to 9
100	10 to 13
200	15 to 18
500	25 to 29
1, 000	36 to 41
2, 000	53 to 58

[a] These values are the limiting computed depths of indentations obtained on specimens initially surface-finished by three different methods (grinding, buffing, and metallographic polishing) and on companion specimens reduced in thickness 1, 2, and 4 percent by cold-rolling.

The depth of the indentations which indicated "softening" of the surface metal during cold-rolling can be calculated, since the depth of the Knoop indentation is linearly related to the length of its long axis (ratio 1:30). The average values for the limiting depth of penetration for the specimens tested, before and after rolling, are listed with the corresponding test load in table 2. A correlation of these values with the Knoop hardness data (table 1) for each load condition suggests that the depth of the metal which significantly decreased in hardness (penetrated with 50, 100, 200, and in some cases 500 grams) during cold-rolling was less than 0.0003 inch.

Although the trends of the results (Knoop tests) were the same for the surfaces investigated, it is noteworthy that the hardness decreases appear more pronounced for the polished specimens than for those which were buffed and ground. An apparent cause for this difference is suggested by the difference of the microstructures of the surface layer of the specimens (fig. 1), which show evidence of cold work (darkened edge) for the buffed and ground specimens but not for the polished ones. The work of Wulff [9] suggests that the layer of disturbed metal due to metallographic polishing is very thin (less than 0.00003 inch). However, Thomassen and McCutcheon [11] have shown that the disturbance produced in metal during the preparation of specimens preliminary to polishing (see surfacing treatment No. 3) is not completely removed by a single polishing treatment such as used in the present study. This condition, although not detectable in the micrographs (fig. 1, *a* and *b*), probably is sufficient to obscure variations expected from very thin layers of disturbed metal developed

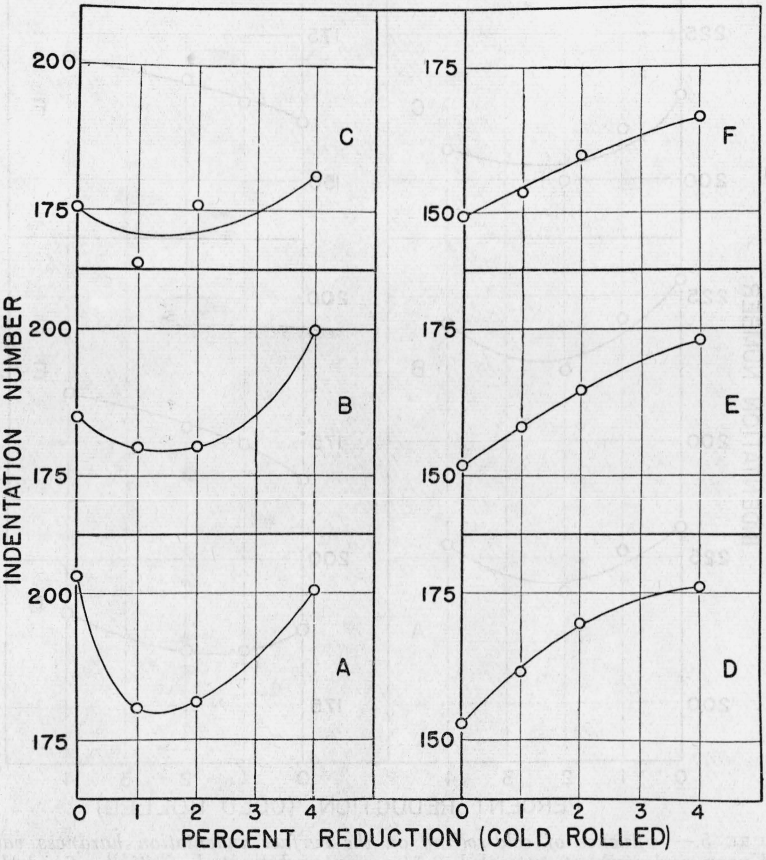

FIGURE 4.—*Influence of cold-rolling on the surface indentation hardness values (Knoop indenter) of annealed 0.34-percent-carbon steel, initially finished by buffing.*

The loads on the indenter (in grams) for the respective curves were as follows: *A*, 50; *B*, 100; *C*, 200; *D*, 500; *E*, 1,000; *F*, 2,000.

by polishing only. Therefore, the distinctive microstructural features of the surface layer of the specimens finished by different means, disclosed in figure 1, may not be conclusive as an explanation for the hardness differences noted. Another factor which may have had a bearing on these results is the geometric characteristics of the surface, which differed for the specimens finished by the different methods. (See profiles, fig. 1.) The significance of this factor with respect to its influence on the depth of penetration of the Knoop indenter has been discussed in a previous publication [1].

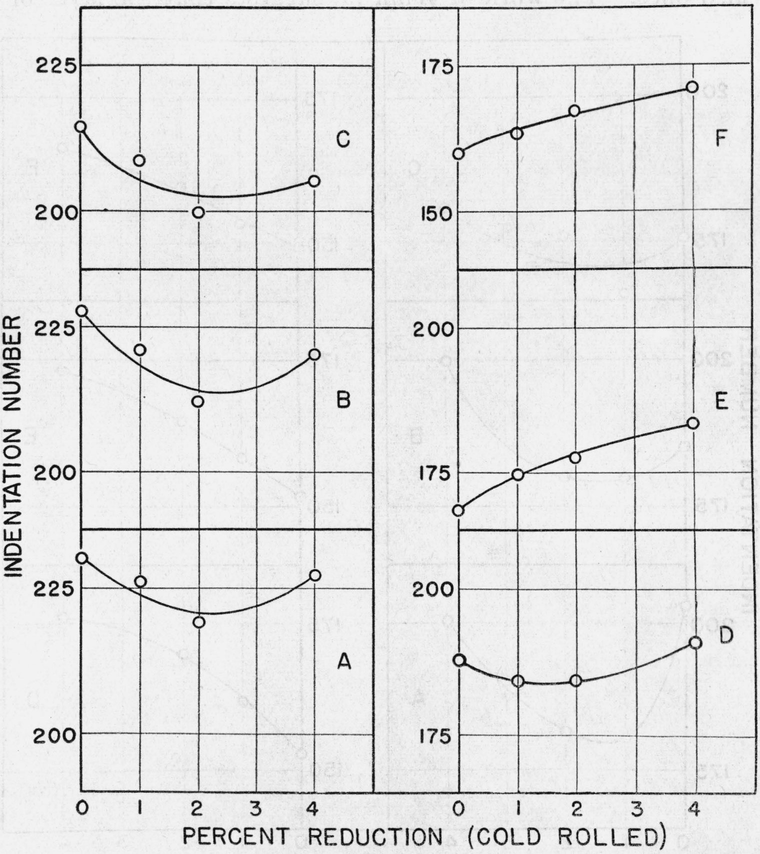

FIGURE 5.—*Influence of cold-rolling on the surface indentation hardness values (Knoop indenter) of annealed 0.34-percent-carbon steel, initially finished by grinding.*

The loads on the indenter (in grams) for the respective curves were as follows: *A*, 50; *B*, 100; *C*, 200; *D*, 500; *E*, 1,000; *F*, 2,000.

The present investigation has not advanced sufficiently to warrant an explanation of the underlying cause of the reversals observed. However, the work of Wood [12] and McAdam and Mebs [13] may be significant in this connection. Wood demonstrated that continuous rolling of metals, particularly of copper, causes an increase in diameter of their X-ray diffraction rings to a maximum, following which there is a diminution to a minimum, the two processes alternating on further cold-working. He concluded that the progressive expansion of the lattice accompanying cold work was indicative of cumulative internal stress and that the contraction was associated with the relief of such stress. McAdam and Mebs have shown in certain cases evidence of the relief of internal stress in severely cold-worked steel after the application of tensile stresses producing slight plastic extensions (0.001- to 0.003-percent permanent set). The results cited suggest the possibility of stress relief induced by the cold-rolling treatments as a significant factor in causing the hardness reversals observed. This presupposes that the surface layer was internally stressed during the polishing, buffing, or grinding treatment. It appears reasonable to assume that such was the case, since it is well known that the surface layer of a metal during mechanical finishing is severely stressed to accomplish the plastic flowing and removing of surface metal characteristic of these treatments.

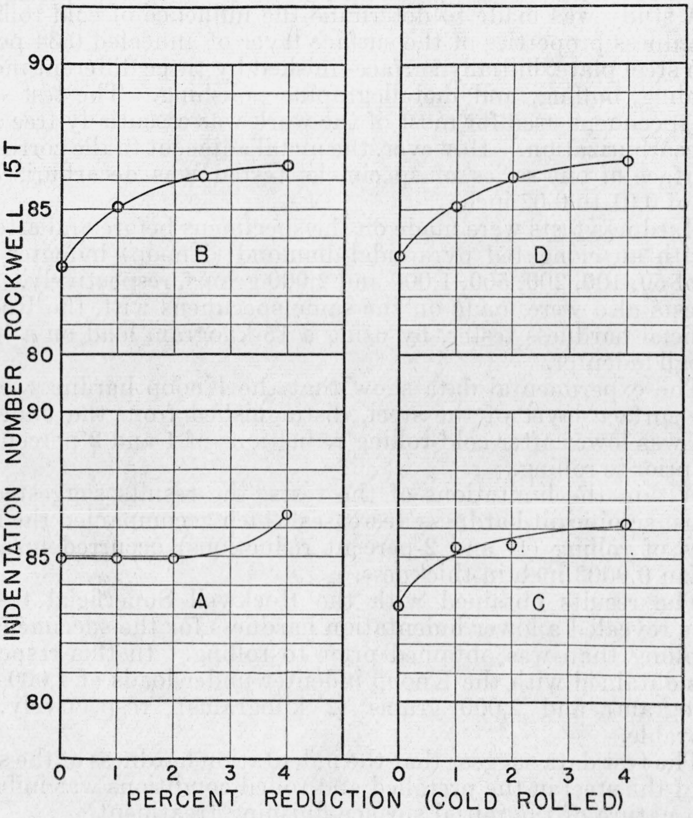

FIGURE 6.—*Influence of cold-rolling on the surface indentation hardness values of the test specimens described in the lengends of figures 2 to 5, as determined with the Rockwell Superficial hardness tester, 1/16-inch ball indenter, 15-kilogram load.*

The initial surface finishes for the respective curves were as follows: *A*, polished (surface layer decarburized); *B*, polished; *C*, buffed; *D*, ground.

The possible annealing effect on the surface layer by the heat generated during rolling should be considered in any theory advanced to explain the fundamental cause of the results obtained. However, this does not propose that such factor is independent of the suggested stress-relief effects which may be a manifestation of annealing reactions. A wholly satisfactory explanation of the phenomenon observed will require further study.

V. SUMMARY

1. A study was made to determine the influence of cold-rolling on the hardness properties of the surface layer of annealed 0.34-percent-carbon steel plate, initially surface-finished by three different methods —grinding, buffing, and metallographic polishing. The test surface of the specimens used for most of the work was essentially free of surface decarburization. However, the metal adjacent to the corresponding surface of one series of specimens tested was decarburized to a depth of 0.01 to 0.02 inch.

2. Hardness tests were made on the specimens before and after rolling, with an elongated pyramidal-diamond (Knoop) indenter under loads of 50, 100, 200, 500, 1,000 and 2,000 grams, respectively. Hardness tests also were made on the same specimens with the Rockwell Superficial hardness tester, by using a 15-kilogram load on a ⅟₁₆-inch steel-ball indenter.

3. The experimental data show that the Knoop hardness number of the surface layer of the steel, distinguished from the underlying metal, was lower after cold-rolling reductions of 1 and 2 percent than it was prior to rolling.

4. Within the limitations of the tests, the results suggested that the most significant hardness decreases which accompanied the lighter degrees of rolling (1- and 2-percent reductions) occurred in a layer less than 0.0003 inch in thickness.

5. The results obtained with the Rockwell Superficial tester in no case revealed a lower indentation hardness for the specimens after cold-rolling than was obtained prior to rolling. In this respect the results obtained with the Knoop indenter under loads of 1,000 grams (1 kilogram) and 2,000 grams (2 kilograms), respectively, were comparable.

6. The test data suggest that the indentation hardness of the surface layer of the steel in the prerolled and rolled conditions was influenced by the nature of the initial surface-finishing treatment.

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