

GRAIN-GROWTH IN DEFORMED AND ANNEALED LOW-CARBON STEEL.

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Considerable attention has been given in recent years to the phenomenon of coarse crystallization or grain-growth in pure iron and low-carbon steels permanently deformed and annealed. While grain-growth may occur in certain other metals and homogeneous alloys, under similar conditions, iron is worthy of special attention because of certain physical properties influencing grain-growth which it possesses, and more particularly because of its extensive use commercially.

Not a little difficulty has faced workers in such materials as sheet, wire, cold-drawn bar stock, and pressings of low-carbon steel. From time to time mysterious epidemics of brittleness in the material would be encountered, breakage occurring under ridiculously small stresses, accompanied by coarsely grained fractures. Annealing often seemed to aggravate the difficulty. Material which passed safely through the various fabricating processes was often put into service under a shroud of fear that it would "crystallize in service."

Fortunately, most of the factors determining these irritating conditions have gradually become known, and it is the purpose of this Paper to state the results of a rather extended investigation covering the subject, and to explain the conditions under which grain-growth occurs. Methods will be suggested by which this trouble may be prevented or cured in general, and for each material investigated in particular, and general conclusions with regard to the phenomenon noted in the investigation will be given.

Historical.

The occurrence of coarse crystallization in low-carbon steel at low temperatures was first mentioned by Stead (1), who observed it "in certain steels and pure irons, originally of fine grain produced by forging or certain heat treatment," when annealed between 500° C. (930° F.), where slow growth occurred, and at 600° to 750° C. (1,110° to 1,380° F.), where the growth was more rapid. Annealing at 700° C. (1,290° F.) for a few hours produced exceedingly coarse grains. Grain-growth was also observed in sheets containing 0.05 to 0.12 per cent. carbon. One peculiarity noted was that grain-growth was never observed in sheets of a gauge less than 18 (2). Experiments to produce the structure at will were not invariably successful.

Charpy (3) showed that a coarse granular structure could be produced in steel low in carbon and phosphorus by pressing the material in a screw plate and subsequently annealing at 700° C. (1,290° F.). He obtained grains about ten times the original size; by proper selection of the annealing temperature and time extremely large grains could be produced.

Sauveur (4) produced the same condition in low-carbon steel, deforming the metal by tension, compression, bending, and in the Brinell hardness testing machine, subsequently annealing his specimens below the thermal critical range. The existence of three zones of crystallization corresponding to the amount of strain was observed. Sauveur came to the conclusion that a definite or "critical" strain was necessary in order to produce grain-growth on annealing. In other investigations the strain necessary to produce grain-growth has been found to cover a rather wide range. The narrow limits noted by Sauveur are probably due to his use of annealing temperatures altogether below the thermal critical range.

Chappell (5) investigated the phenomenon in somewhat the same way as Sauveur by means of Brinell impressions and by pressing, by gradual stages, a single groove along the centre of a bar and sectioning the bar along the groove. For greater convenience in handling, grooves were also impressed at intervals across the bar. These bars were heated at one end in a furnace, the other end being kept cool in the air, care being taken to insure a regular fall of temperature along the bar, thus permitting the study of the temperature variable. In order to determine the quantitative effect of deformation, tension to fracture was applied to tapered bars, which were then annealed at various temperatures. The effect of deformation at high temperatures was investigated, and exceedingly coarse grains produced by subjecting the material to stress at 870° C. (1,600° F.) and then annealing at about 850° C. (1,560° F.). No occurrence of coarse crystallization was noted in annealed cold-drawn wire, this condition being produced only in pure iron that had received local deformation. It is stated, however, that the negative result is probably due to the wire having been strained beyond the limiting range. The effect of bending under shock was also tested. In cases of local deformation Chappell notes the existence of three zones after annealing within a certain range: one representing a high degree of deformation in which there is no appreciable change in the crystals; a central zone of moderate deformation in which there is a large crystalline growth; and a third zone of little or no deformation in which there is no growth, a result which corresponds closely to that obtained by Sauveur. It is stated that the highly deformed inner zone is not one in which no change takes place on annealing, but a zone in which the recrystallization takes place at a lower temperature than that of the outer zone. With regard to the quantitative effect of deformation and the temperatures within which recrystallization occurs, Chappell states that "Plastic strain in practically every degree produced recrystallization on annealing below A_3 ," and also that, "Given sufficient time the major part of the recrystallization is complete at 700° to 750° C., and in its incipient stages may commence as low as 350° C."

The influence of carbon, according to the investigation, is to restrict the size of the crystals developed and to make a higher degree of stress necessary to produce growth and also to lower the temperature at which the gross crystallization is destroyed. This conclusion was arrived at as a result of the examination of a bar of 0.30 per cent. carbon steel, which was turned down into a double cone-shaped test-piece similar to the tapered tensile test-pieces mentioned. This bar was then partially decarbonized by ore annealing, and after cooling was pulled to fracture and sectioned down the centre. One half was then heated at progressively higher temperatures between 600° and 900° C. by 50° intervals, thus permitting a study of the effect of the three variables, carbon, strain, and temperature, with one test-piece.

Some years ago the writer had occasion to investigate the occurrence of coarse crystallization in low-carbon steel in various commercial forms and

published a brief account (6) of part of this work. This investigation has been continued with several commercial varieties of cold-worked low-carbon steel, largely under commercial conditions.

The materials investigated were hot-rolled rod, cold-drawn wire, hot- and cold-rolled sheet, cold-rolled strip, cold-drawn tubing and pressings, the principal commercial forms of low-carbon steel in which coarse crystallization occurs. The effects of forging hot and cold were investigated on a small scale by the use of a hand hammer on small test-pieces. The quantitative effect of permanent deformation received special attention.

Conditions under which Grain-growth occurs.

The formation of coarse grains in low-carbon steel will follow the action of a limited amount of stress exceeding the elastic limit, or in other words, limited permanent deformation, and subsequent annealing within certain temperature ranges. This has been confirmed by all investigators of this phenomenon. In the writer's earlier investigations certain other phenomena depending upon the quantitative effect of permanent deformation were observed, and have been confirmed by the later investigations. On varying by narrow steps the amount of applied stress within the range mentioned, it was noted that the less the permanent deformation the greater was the grain-size on subsequent annealing. Within the limiting range of strain and near the lower limit there seems to be a definite or "critical" strain, below which the range of temperature within which grain-growth will occur is limited by the A_{r1} , A_{r2} thermal critical points, about 690° and 780° C. ($1,275^{\circ}$ and $1,435^{\circ}$ F.). When the material is strained beyond this point, the annealing range is considerably extended, falling between about 650° and 900° C. ($1,200^{\circ}$ and $1,650^{\circ}$ F.). The moderate grain-growth occurring below 650° C. ($1,200^{\circ}$ F.) noted by other investigators was not found in this investigation. This "critical" strain mentioned has not been definitely observed by other investigators, although Chappell's statement mentioned (that the highly deformed inner zone is not one in which no change takes place on annealing, but a zone in which the recrystallization takes place at a lower temperature than that of the outer zone) may be taken as partial confirmation of its existence. The quantitative effect of strain on the grain size has also been partly confirmed by Chappell's work.

Standards of Measurement.

In order to study the effect of permanent deformation quantitatively it was necessary to find some fairly accurate and convenient standard of measurement, direct if possible, but at least relative. Measurement of the stress applied beyond the elastic limit is of course direct, but is applicable only when applied in tension or compression in such a way that this may be determined, and, in commercial cases particularly, offers neither a convenient nor a practical standard. On this account the more convenient and relatively accurate reduction of area was adopted. This can be determined easily and with reasonable accuracy in a large number of commercial operations, as, for instance, the rolling of strip steel or the drawing of wire, where the measurement of the applied tensile stress would be impossible. As it is necessary to exceed the elastic limit in order to produce grain-growth, the reduction of area, with its origin at the elastic limit, is also a more relatively accurate standard of measurement. In certain cases, of which some pressing operations to be discussed are typical, the nature of the strain may be so complicated that no simple standard of measurement will serve to define it, and

some purely relative and empirical standard must be adopted. In many such cases, however, the reduction of area will serve as a basic standard.

Experimental Operations.

Forging and Hot Rolling.—A number of samples of hot-rolled rod of about $\frac{1}{2}$ in. diameter, found to be fine-grained after annealing within the critical range, were forged under widely varying conditions, annealed, and examined. The forging was carried on by means of a hand hammer, and all the samples were finally annealed at 700° C. (1,290° F.). Certain samples were heated to temperatures above 900° C. (1,650° F.) and hammered; the temperature at which work ceased was estimated by some approximate means, such as colour in semi-darkness or by the scorching effect on wood. Other samples were hammered cold. Where grain-growth was found it was usually confined to a narrow area about $\frac{1}{16}$ in. wide at the periphery of the piece. As nearly as could be determined by the rather crude method of measurement, no grain-growth occurred unless the rod was forged below a temperature somewhere between 650° and 750° C. (1,200 and 1,380° F.). Some of the results are given in Table I.

TABLE I.

Forging Tests on Hot-rolled Rod.

	Rod diameter $\frac{7}{16}$ in.					Grain-size in mm. at edge after 1 hour at 700° C.
Original rod	·02
Forged cold	·40 to ·16
Forged cold	·30 to ·18
Forged from 900° C. to red	·02
Same. Spot next to anvil	·22 to ·40
Forged from 900° C. to black	·14 to ·22
Forged from 900° C. to about 500° C.	·14 to ·40
	Rod diameter $\frac{9}{16}$ in.					
Original rod	·02
Forged cold	·22 to ·40
Forged cold	·18
Forged from 900° C. to red	·02
Forged from 900° C. to black	·18 to ·40
Forged from 900° C. until cold	·10
Forged from 900° C. until cold	·08

No case of grain-growth was observed in annealed samples of hot-rolled rod, of which a considerable number were examined.

Cold-drawing.—Samples of hot-rolled rod of from $\frac{1}{4}$ to $\frac{1}{2}$ in. diameter were cold-drawn to various sizes, and samples from each draft annealed at temperatures between 650° and 900° C. (1,200° to 1,650° F.). No grain-growth was found outside of this temperature range. In a number of tests the amount of reduction was varied by as narrow steps as possible, in some cases 0·001 in. For reasons which will be made evident, the samples in each set which were annealed at 700° C. (1,290° F.) were selected for the determination of the quantitative effect of strain. Some of the results are given in Table II. From these it will be seen that, within certain limits, the grain-size after annealing is inversely proportionate to the applied strain.

TABLE II.

Grain-sizes of Annealed Cold-drawn Rods.

Diam. In.	Diam. after draw. In.	Red. Area, per cent.	Grain-sizes, mm., 1 hr. at 700° C.	Grain-size, mm., 1 hr. at 800° and 850° C.
'386	'372	7	'02	'02
'386	'368	9	$\frac{1}{2}$ '02, $\frac{1}{2}$ '30 to '52	'02
'386	'3645	11	'27, a few '02	'27 to '02
'386	'3595	13	'15	'15
'312	'302	7	'52	'02
'312	'296	10	'10	'10
'312	'289	15	'06	'06
'312	'280	20	'04	'04
'312	'271	25	'036	'036
'384	'336	7	'02	'02
'384	'334	8	'50	'02
'384	'332	9	'40	'02
'384	'330	10	'22	'22
'351	'342	5	'02, a few '12	'02, a few '12
'351	'339	6.5	'02	'02
'351	'338	7	'52 to '72, a few '02	'02
'351	'336	8	'28 to '50	'02
'351	'334	9	'40	'20 to '40
'385	'375	5	'02	'02
'385	'373	6	'02	'02
'385	'371	7	'02, a few '20	'02
'445	'429	7	'02, some '14	'14-'02
'372	'361	6	'02	'02
'351	'334	9	'50	'02
'351	'324	15	'14	'14
'351	'315	20	'05	'05
'351	'304	25	'03	'03
'437	'415	10	'20	'20
'437	'404	15	'12	'12
'437	'392	20	'04	'04
'437	'379	25	'03	'03
'486	'452	7	'02	'02
'486	'445	10	'27	'27 to '02
'486	'432	15	'12	'12
'486	'419	20	'05	'05
'439	'416	10	'40	'02
'439	'410	15	'17	'17
'439	'392	20	'05	'05
'498	'472	10	'22 to '35	'22 to '35
'498	'460	15	'11	'11
'498	'450	20	'05	'05

On examining the samples annealed at various temperatures between the limits mentioned, it was noted that while the more heavily strained specimens showed a grain-growth after annealing within this limiting temperature range, some of these which were more lightly strained became coarsely crystalline only when annealed between about 690° and 780° C. (1,275° to 1,435° F.). Reheating above the latter point would refine any coarse-grained structure that might have been produced in the specimens. Photomicrographs of one of these specimens as annealed at various temperatures between 675° and 780° C. (1,250° and 1,435° F.) are shown in Plate I. A large number of specimens of this material were examined after annealing at the higher temperature, and all were found to be refined with the exception of one small section found on repolishing in which a few moderately coarse grains existed. This section was selected for photographing in order to show the narrow range of deformation within which perfect refining at this temperature probably occurs.

The analysis of this steel is: Carbon, 0.08; manganese, 0.34; sulphur, 0.032; phosphorus, 0.010; and silicon, 0.020 per cent. The reduction of area was probably about 9 per cent.

These results seem to indicate the existence of a "critical" strain affecting the annealing temperature ranges within which grain-growth occurs.

For further confirmation a number of other samples were drawn with varying reductions of area in narrow steps, and annealed at various temperatures between about 650° and 900° C. (1,200° and 1,650° F.). The results obtained with one series are given in Table III and others in Table II.

TABLE III.

Quantitative Effect of Drawing and Annealing Rod 0.320 in. Diameter.

After drawing.		Grain-size in mm. after 1 hour at	
Diam. In.	Red. Area, per cent.	700° C. (1,290° F.)	800-850° C. (1,470-1,560° F.)
.309	6.5	.02	.02
.307	8.0	Some .02; rest .40 to .80	.02
.305	9.0	.28 to .56; a few .02	.02
.303	10.0	.25 to .40; a few .02	.02; some .18
.302	11.0	.20 to .25	.20 to .25
.300	12.5	.15	.15
.297	16.0	.07	.07

The photomicrographs of this series shown in Plate II illustrate the decrease in the grain-size with increase in the amount of deformation as found in the series annealed at 700° C. (1,290° F.). Smaller sections of the samples drawn with 8, 9, 10, and 11 per cent. reduction of area and annealed at 780° C. (1,435° F.) are also shown to illustrate the action of the "critical" strain. It will be noted that the samples show complete refining at this temperature until the reduction of area rises to about 10 per cent., when some coarse crystallization still remains. With heavier reductions no refining occurs until the material is annealed at about 900° C. (1,650° F.). The decrease in grain-size which accompanies increase in strain is also

illustrated in Plate IIA, in which are shown photomicrographs of another series drawn with increasing reductions of area from a rod about $\frac{3}{8}$ in. in diameter.

Some difficulty was encountered in duplicating the results, as the rod was frequently out of round slightly and sometimes varied locally in diameter. The greatest variations were noted in attempts to determine the lowest reduction which would cause grain-growth. Where light reductions were used the effect was frequently confined to the periphery or to local areas, the remainder of the section being unaffected. An example of this will be seen in photomicrograph No. 1, Plate II, showing a specimen annealed at 700° C. (1,290° F.). Occasionally sections were found in which the strain was unevenly distributed, as shown by the wide variation in the grain-size produced. In some lightly strained samples which apparently became refined completely at 780° C. (1,435° F.), a certain "skin" effect was sometimes noted. On examining longitudinal sections of samples annealed at this temperature, a thin layer of moderately coarse grains,

TABLE IV.

Quantitative Effect in Cold-rolling Strip Steel.

Size after Cold-rolling. In.	Red. Area, per cent.	Grain-size in mm. after 1 hour at 700-870° C. (1290-1600° F.)
<i>Hot-rolled strip, .625 in. thick.</i>		
.059	5.6	.034; a few .10
.0575	8.0	.03; a few .14 to .27
.056	10.0	.14 to .28
.0545	13.0	.09 to .14
.053	15.0	.07 to .11
<i>Hot-rolled Strip, .064 in. thick.</i>		
.061	4.5	.02 to .03
.0585	8.5	.02 to .27
.0575	10.0	.21; some .02
.056	12.5	.14
.054	15.5	.10
.0515	19.5	.05 to .08
.049	24.5	.027 to .036

possibly 0.12 to 0.18 mm. in diameter, was sometimes found close to the periphery, the rest of the piece being completely refined. Allowing for these minor variations and using proper precautions, it was generally possible to reproduce these results at will. With the exception of the local effects noted, no grain-growth occurred if the reduction of area fell below about 7 per cent.

In the tabulated results some variations between the different series will be noted. These are generally due to the previously mentioned variation in the conditions of drawing.

Cold-rolled Strip.—A few samples of hot-rolled strip about 0.065 in. thick were cold-rolled with varying reductions of area. The same variation in grain-size with reduction was found with this material as with the cold-drawn steel. Refining took place only at 900° C. (1,650° F.), no "critical" strain being noted. The material was too light for careful measurement, and the

presence of certain irregularities in the surface made impossible an exact determination of the reduction of area. The largest grain-growth produced was much less than that obtained with the cold-drawn specimens, which had received comparatively light reduction. Some of the results obtained were given in the previous article mentioned and are repeated in Table IV. No heavier material was available at the time the investigation was carried out, and further study was confined to a number of cases of coarse crystallization found in strip $\frac{1}{16}$ to $\frac{1}{8}$ in. thick, obtained from various sources. A few cases were found in which complete refining occurred on annealing at $780^{\circ}\text{C. (1,435}^{\circ}\text{F.)}$. In other cases, partial refining occurred at this temperature. In a few cases no refining occurred until the material was annealed at $900^{\circ}\text{C. (1,650}^{\circ}\text{F.)}$. In the cases where complete or partial refinement occurred at 780°C. , the original grain-size varied from 0.52 to 0.65 mm. in diameter. Where 900°C. was required, the grain-size was smaller than this.

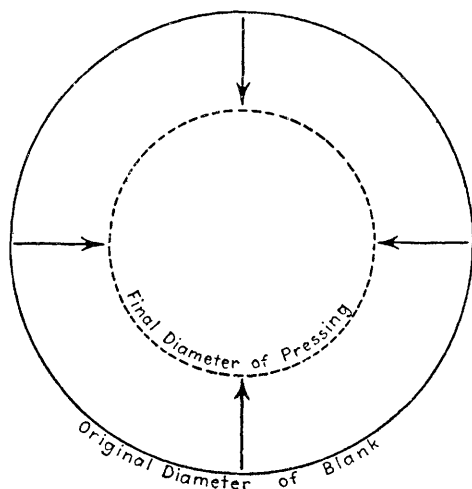


Fig. 1—Circumferences of Blank and of Pressing

FIG. 1.

Cold Pressings.—The quantitative study of grain-growth in low-carbon steel pressings is decidedly difficult if the action of the strain is at all complicated. In certain cases the amount of strain can be determined relatively, as, for instance, in operations such as bending, light drawing, and forming. In a drawing operation such as is shown in Fig. 1, representing a blank and a pressing to be formed, if the operation is carried out with no reduction in the thickness of the metal, the amount of strain can be determined relatively.

In Fig. 1 the outer circle represents the circumference of the blank, the inner circle the circumference of the pressing. In the pressing operation the periphery of the blank becomes the top of the pressing and receives the heaviest strain. The bottom of the pressing receives little or no strain. In the side walls are zones in which the strain increases regularly from the bottom to the top. In the drawing, Fig. 1, these zones are included in the area between the inner and outer circles. The strains existing in these zones can be represented relatively by the frustrum of a cone of the same height as the pressing, the radii of the upper and lower bases being respec-

tively equal to the radius of the blank and the radius of the pressing. In such a figure the radius of the smaller base represents the zero point of measurement. The difference between the radius of the smaller base and the radius of the larger base represents the maximum amount of strain received by the pressing.

Fig. 2 is a diagrammatic representation of the relative strains in a typical pressing operation.

If a pressing of this type is annealed at 700°C . ($1,290^{\circ}\text{F}$.) and examined, it will be found that there has been considerable grain-growth, large at the bottom, and decreasing in size regularly toward the top.

Strips were cut from a number of such pressings and annealed at various temperatures between 600° and 900°C . ($1,110^{\circ}$ to $1,650^{\circ}\text{F}$.). On examining samples annealed between 690° and 900°C . ($1,275^{\circ}$ and $1,435^{\circ}\text{F}$.) it was noted that a sharply defined zone of marked grain-growth occurred near the bottom of the pressing. Near the top of the pressing a zone was found in which the grain-size was normal. In the central zone extending between the bottom and top zones the grain-size decreased gradually until it became normal.

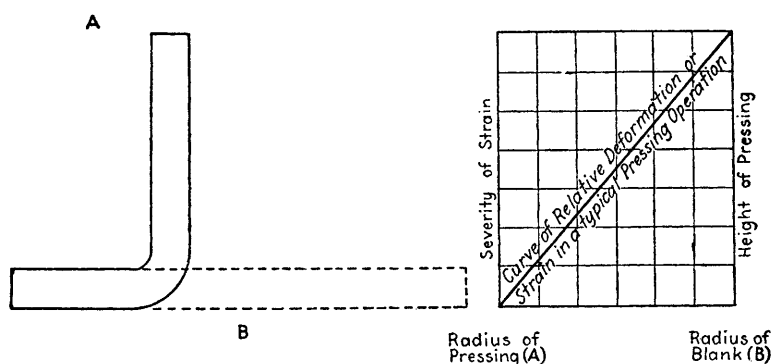
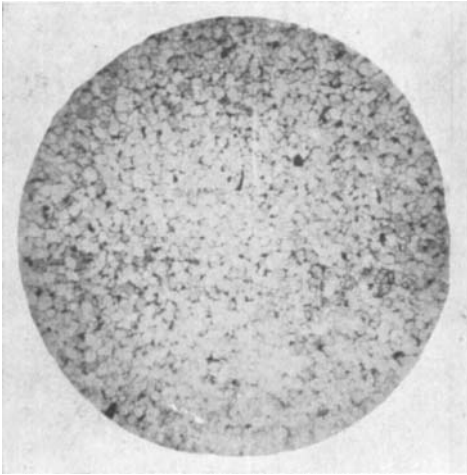


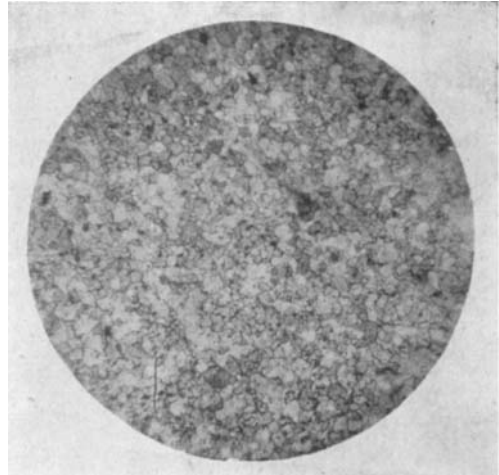
FIG. 2.

No grain-growth occurred at the bottom. On reheating to 790°C . ($1,450^{\circ}\text{F}$.) partial refinement took place in the lower zone. Samples annealed between 780° and 875°C . ($1,435^{\circ}$ and $1,605^{\circ}\text{F}$.) showed rather moderate grain-growth in the lower zone, decidedly less than that obtained on annealing between 690° and 780°C . On annealing below 650°C . ($1,200^{\circ}\text{F}$.) for periods of time up to six hours, no grain-growth was found. On annealing between about 650° and 690°C . no grain-growth occurred in the lower zone and only a moderate growth in the central zone. The photomicrographs in Plate III illustrate the effect of the various annealing temperatures. In preparation for these, parallel strips were cut through the pressing and annealed at the temperatures noted. The photomicrographs represent the same relative position in the pressing. No variation for increase in size was noted.

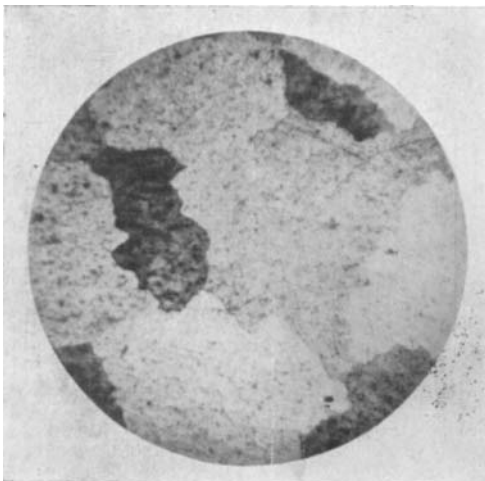
A similar condition was noted on experimenting with a number of pressings of widely varying gauge, which had received moderate drawing, bending, or forming. These results tend to confirm the existence of the "critical" strain noted in the experiments with the cold-drawn steel. That refining occurs at about 780°C . ($1,435^{\circ}\text{F}$.) was noted in actual practice with many pressings in which the presence of coarse grains had prevented further operations. After annealing at about 790°C . ($1,450^{\circ}\text{F}$.) the metal could be



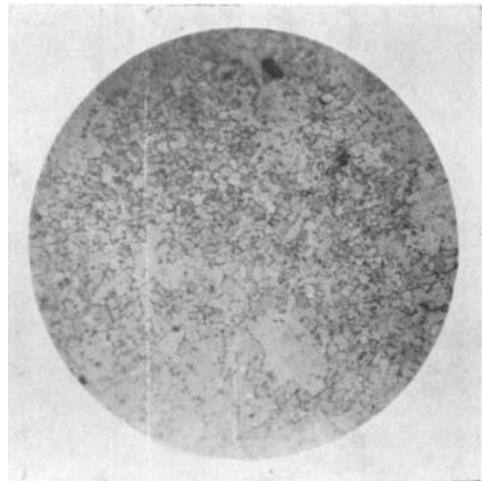
Original rod annealed 1 hour 700° C.



After drawing. Annealed 1 hour 675° C.

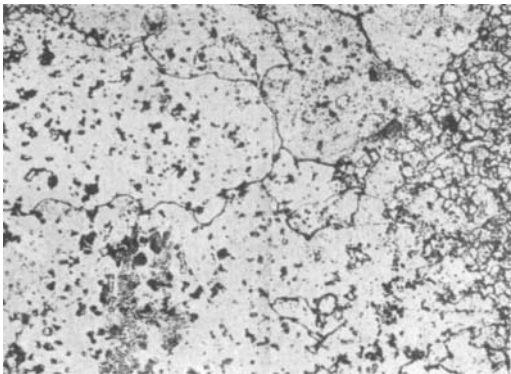
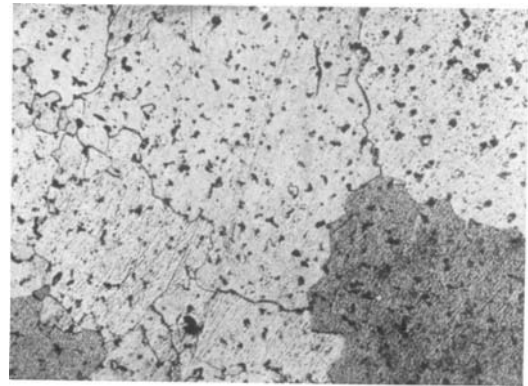


After drawing. Annealed 1 hour 700° C.

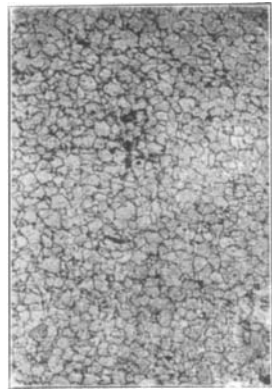


After drawing. Annealed 1 hour 780° C.

PLATE I.—Result of annealing rod drawn about 9 per cent. reduction of area. 50 diameters



Annealed 1 hour 700° C.



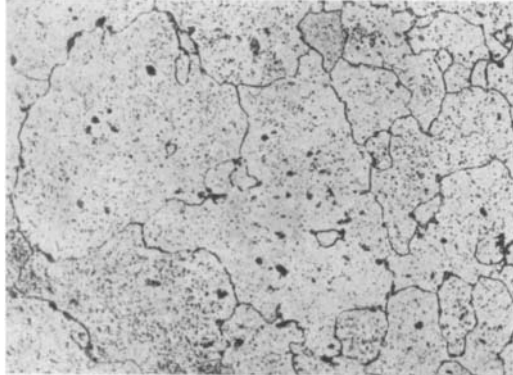
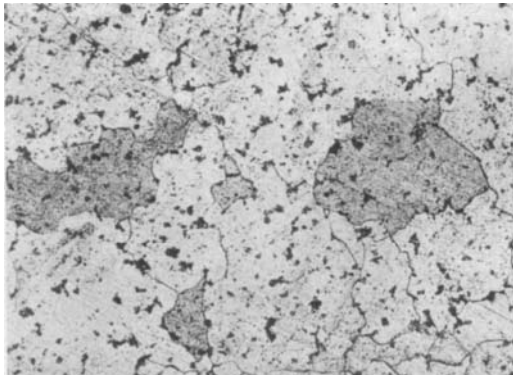
9 per cent. reduction of area.



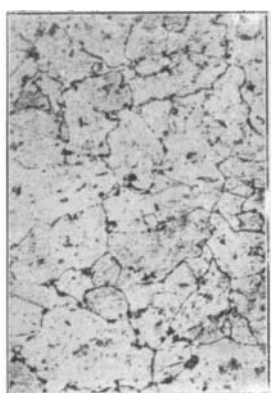
per cent. reduction of area.

Annealed 1 hour 790° C.

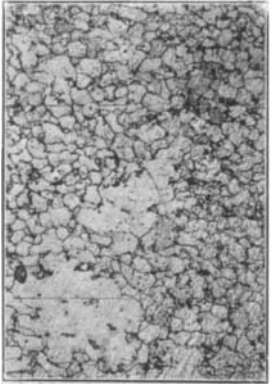
PLATE II., Sheet 1.—Rod 0.320 in. diameter. Drawn. All 100 diameters. Reduced by 1.



Annealed 1 hour 700° C.



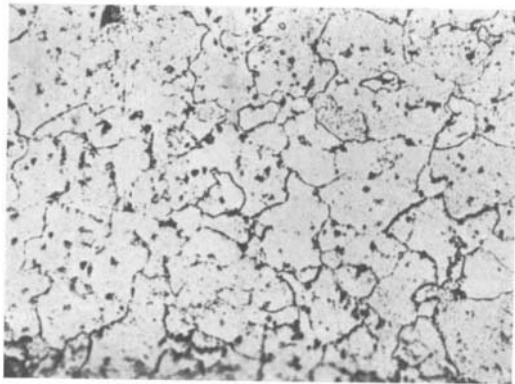
11 per cent. reduction of area.



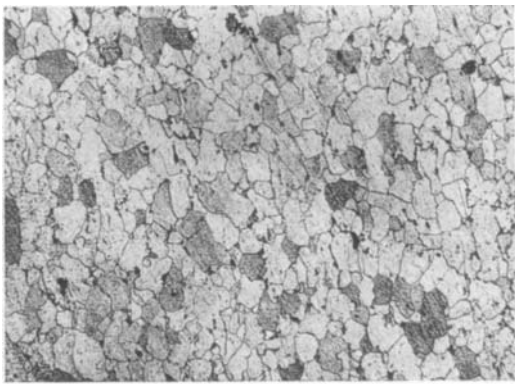
10 per cent. reduction of area.

Annealed 1 hour 790° C.

PLATE II., Sheet 2.—Rod 0.320 in. diameter. Drawn. All 100 diameters. Reduced by $\frac{1}{3}$



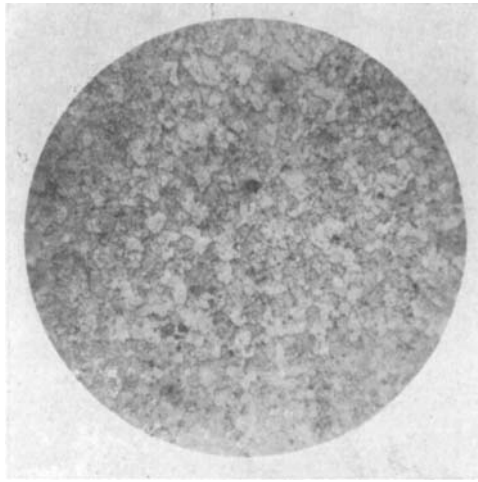
12·5 per cent. reduction of area.



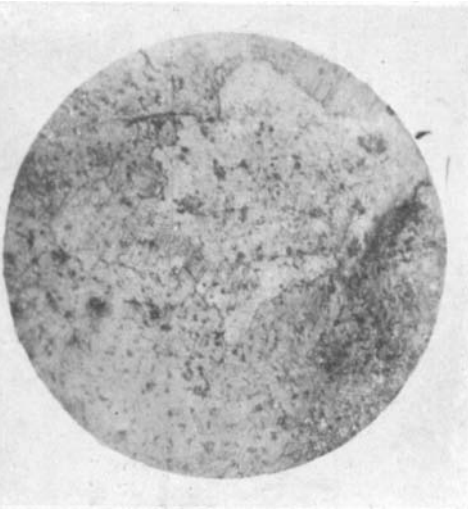
16 per cent. reduction of area.

Annealed 1 hour 700° C.

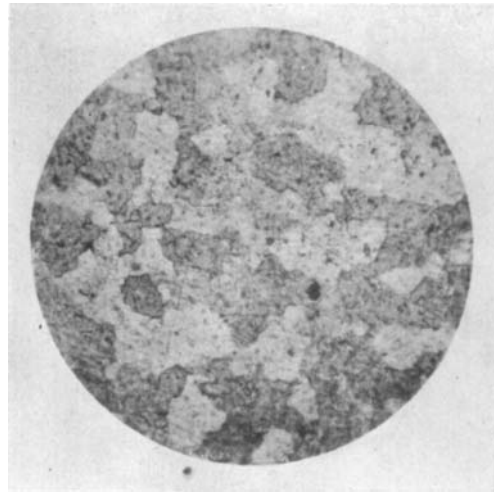
PLATE II., Sheet 3.—0·320 in. rod. Drawn. 100 diameters. Reduced by $\frac{1}{3}$.



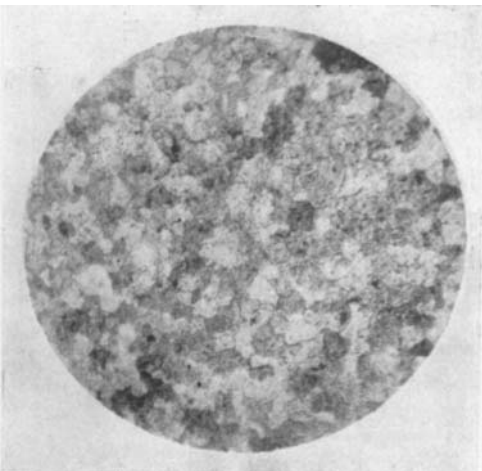
Original rod.



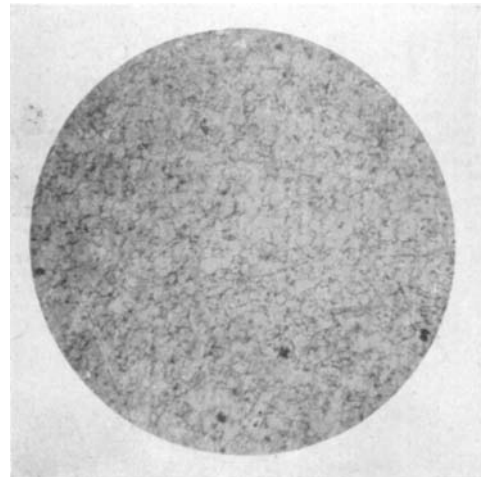
9 per cent. reduction of area.



14 per cent. reduction of area.



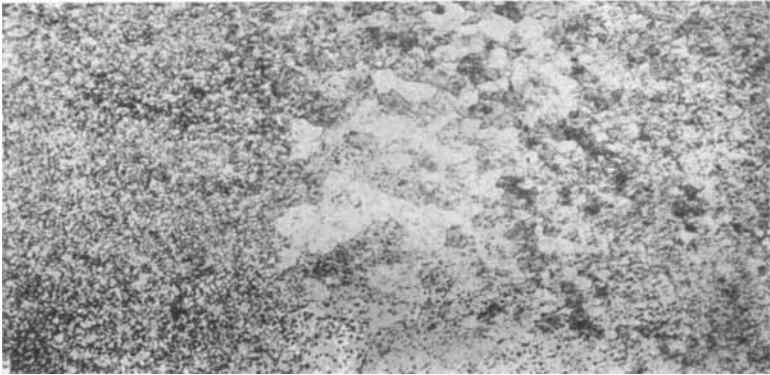
20 per cent. reduction of area.



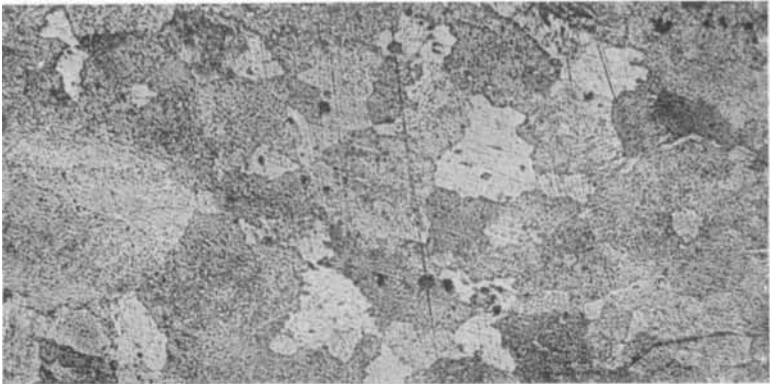
25 per cent. reduction of area.

PLATE 11A.—Effect of varying reductions in cold drawing. Rod about $\frac{3}{8}$ in. All annealed 1 hour 700°C . All 50 diameters. Reductions approximate.

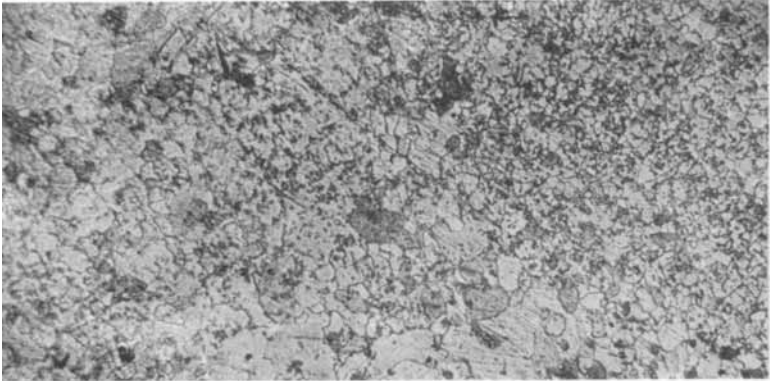
Bottom of pressing.



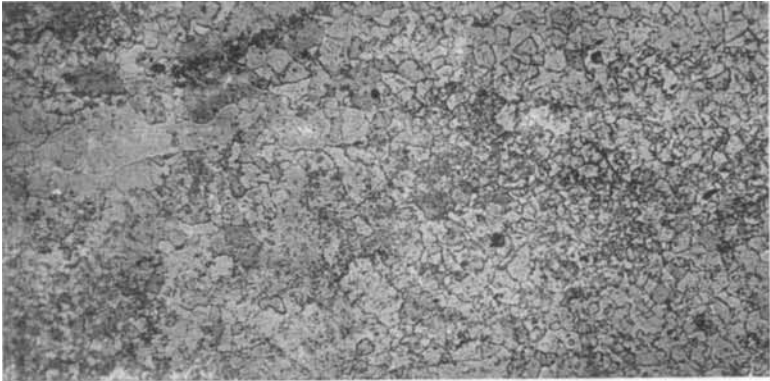
Annealed 675° C.



Annealed 705° C.



Annealed 790° C.



Annealed 795° C. Reheated to 790° C.

PLATE III.—Parallel strips cut from pressing. Annealed $\frac{1}{4}$ hour. 25 diameters.

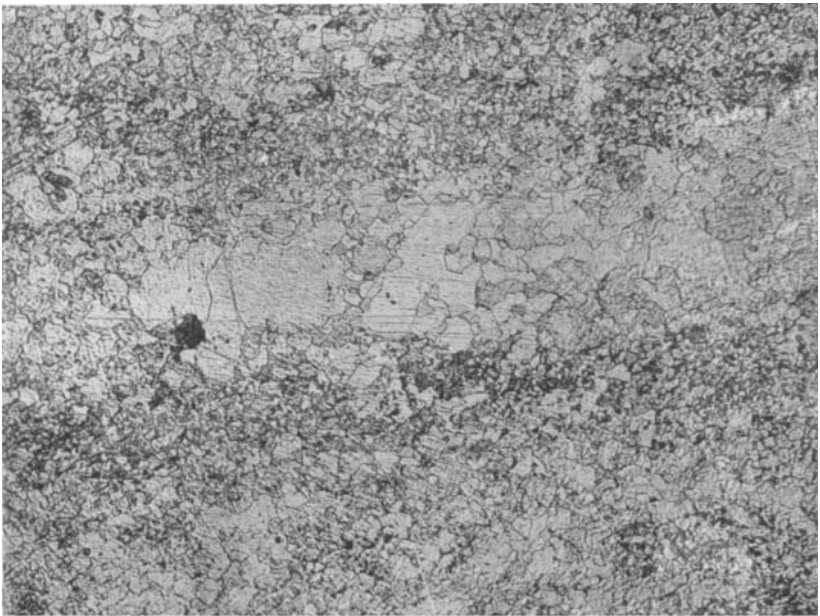
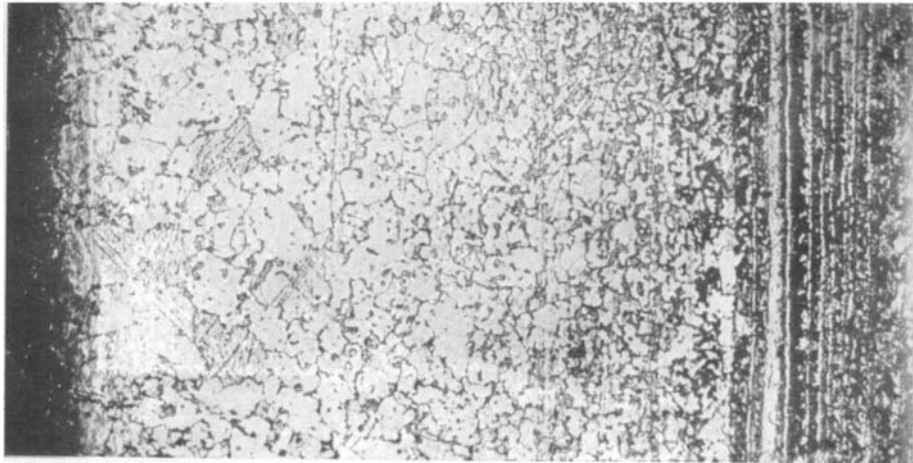
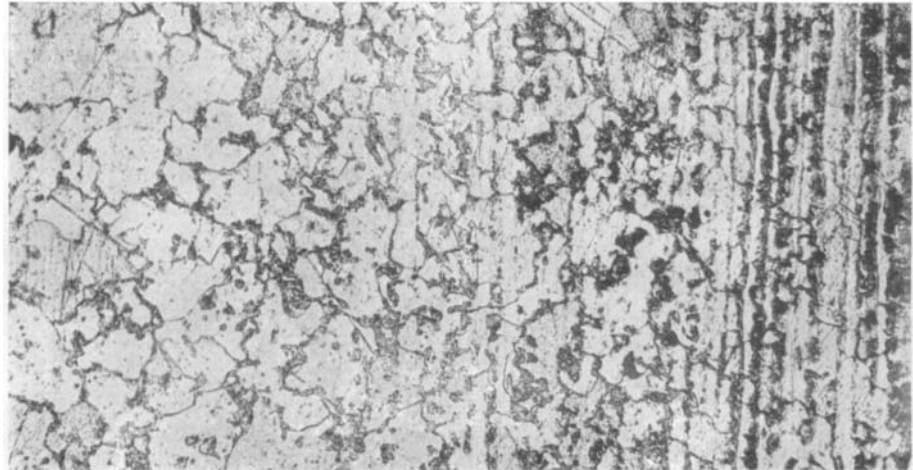


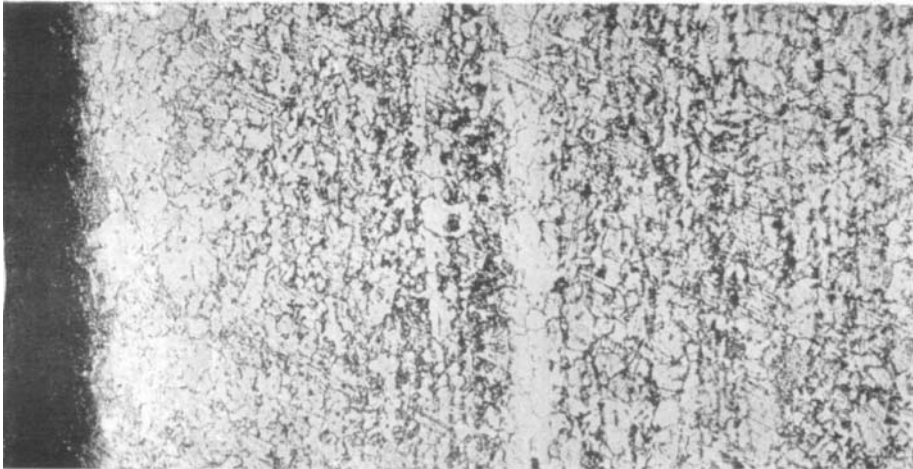
PLATE IV.—Grain-growth in ferrite band of hot-rolled sheet, 0.18 carbon.
100 diameters.



0.21 carbon steel. 50 diameters.



0.21 carbon steel. 100 diameters.



0.17 carbon chrome-nickel steel. 100 diameters.

PLATE V.—Effect of carbon on grain-growth.

Photomicrographs showing grain-growth in decarbonized surface and in ferrite bands of pressings annealed for 1 hour at 795° C.

readily worked. In a comparatively small number of cases where the operation to be performed was somewhat severe, it was necessary to anneal at 900° C. (1,650° F.).

Effect of Carbon.

The observations of nearly all the investigators of the subject tend to show that grain-growth to any appreciable extent will not occur in steel that has a carbon content uniformly above 0.15 to 0.18 per cent. While no exact determination was made, this was practically confirmed in this investigation. Grain-growth was observed in certain cases in steels of from 0.18 to 0.20 per cent. carbon, but only in the ferrite bands present. A photomicrograph of a case of this kind is shown in Plate IV. Where no ferrite bands were present and the steel was uniformly 0.18 per cent. or higher in carbon content, no appreciable grain-growth was observed. The results of microscopical examination were confirmed by the results obtained in commercial practice. In several cases where coarse crystallization proved to be a serious factor in the manufacture of pressings of low-carbon steel, the difficulty was eliminated by the use of steel containing about 0.20 per cent. of carbon.

A study was made of some pressings from $\frac{1}{8}$ in. plate which was slightly decarbonized on the surface. Two varieties of steel were examined, one a 0.20 per cent. carbon steel of ordinary basic open-hearth analysis, and the other a chrome-nickel steel of the following analysis:—

Carbon	...	...	...	...	...	...	0.17 per cent.
Manganese	...	...	...	...	...	...	0.60 "
Sulphur	...	...	...	...	...	...	0.038 "
Phosphorus	...	...	...	...	...	...	0.018 "
Nickel...	...	...	...	...	...	...	1.0 "
Chromium	...	...	...	...	...	...	0.42 "

After the pressing operation, which consisted in forming from the blank a cup-shaped pressing about $2\frac{1}{4}$ in. high and 3 in. in diameter, with a slightly flanged top, strips were cut from the top to the bottom and annealed for one hour at 705° C. (1,300° F.). Photomicrographs of a set of these strips are shown in Plate V. No. 1 represents the edge of the carbon steel pressing (40 diameters); No. 2 is part of the same section enlarged to 100 diameters; No. 3 represents the section from the edge of the chrome nickel steel pressing (100 diameters).

The effect of increasing carbon content is quite strikingly shown in these specimens. In the decarbonized layer the grain-growth, while not exceedingly large, is very marked and appears to some degree in the ferrite bands. In narrow ferrite bands grain-growth to any appreciable degree appears to be checked between the pearlite walls and is frequently shown only by the elongation of the grains between the walls. Wherever the pearlite is present in sufficient quantity to surround the grains, no appreciable grain-growth seems to occur. In the wider ferrite bands there is usually more appreciable growth.

There are a number of factors which make the study of the effect of carbon by the use of decarbonized steels rather difficult, and, to eliminate as many of these as possible, some other method of procedure becomes necessary. It should be possible to obtain excellent results by preparing a series of steels of varying carbon content in the form of hot-rolled rod, drawing each individual rod with varying reductions of area. Because of the greater possibility of control of the variable factors, this method would permit of a more accurate study of the effect of carbon.

Examination of the chrome-nickel steel pressing, which was only slightly decarbonized, showed that while grain-growth occurred, it was of less extent than in the carbon-steel pressing. The pressings were alike, being made with the same die and punch. Grain-growth was generally of greater extent in the ferrite bands than in the surrounding areas, and the growth in some of the larger ferrite bands was practically of the same extent as in the surface layer. The same suppression of growth in the presence of pearlite was noted, although not quite so marked, possibly owing to the lower carbon content.

Analysis of the Steels.—The carbon content of the various carbon steels examined during this investigation varied from 0.05 to 0.18 per cent. All were basic open-hearth stock, with the usual content of other constituents.

Physical Properties.

While the most noticeable difference in the physical properties of normal and coarse-grained low-carbon steel is in resistance to shock, some marked differences were noted in the tensile properties. While these may vary in sheet according to the conditions of rolling, the presence of coarse grains usually caused a lowering in the elastic limit and in the elongation. Some

TABLE V.

Properties of some Coarse-grained Hot-rolled Sheet.

Thickness, in.	E. L., lb. per sq. in.	M. S., lb. per sq. in.	Elong., 2 in. per cent.	Grain- size, mm.
.096	23,000	46,000	33	.20
.093	26,300	50,000	36	.10
.095	23,000	47,200	38	.15
.074	24,000	45,000	36	.08
.064	24,600	46,000	36	.10
.067	26,000	48,700	35	.12
.122	24,700	47,000	36	.12

instances are given in Table V. Under normal conditions the physical properties of hot-rolled sheet were found to be as follows: Elastic limit, 30,000 to 35,000 lb. per square inch; maximum strength, 45,000 to 50,000 lb. per square inch; elongation in 2 in., 42 to 52 per cent.

Duplicate samples from the same sheet usually gave similar results. After annealing at 900° C. (1,650° F.), the tensile properties became quite normal. Similar changes in physical properties were noted in coarse-grained cold-drawn and cold-rolled material.

Time Effect.

The effect of increasing the time of annealing was investigated, but no increase in the grain-size due to prolonged annealing was found. Samples were annealed for varying periods of time up to eight hours. Some difference was noted in the time required for cold-drawn steel and for the light pressings. One half-hour was required to produce grain-growth in the drawn material, while in thin pressings a few minutes was sufficient.

Thermal Critical Points.

Thermal critical points were determined with a coarse-grained sample from a large pressing, the stock being $\frac{1}{2}$ in. plate, basic open-hearth, 0.05 per cent. carbon. The stock was originally of fine grain, but had become very coarse-grained during the pressing and annealing operations, the grains in some cases being as large as 0.9 mm. The Leeds and Northrup apparatus for the determination of transformation points was used for this purpose, the resistance being kept low in order to make small changes noticeable. A slight change was noted at the A_1 points. At about 775° C. (1,430° F.) a marked change was found in the first heating curve, the differential marker leaving the field entirely. The Ac_3 point was very marked at about 910° C. (1,670° F.). On cooling the transformation points were not so marked. The Ar_3 point appeared at about 880° C. (1,615° F.) and the Ar_2 point at about 775° C. (1,430° F.). The sample was reheated several times to note changes that might occur in the location or the intensity of the transformation points. The intensity of the points Ac_2 and Ac_3 was much diminished on the second heating, while that of the Ar points remained about the same. The location of the various points was unchanged.

Coarse Crystallization in Commercial Materials.

Sheet and Strip Steel.—The occurrence of a coarse-grained structure is common in both hot-rolled and cold-rolled annealed sheet. In the former no grain-growth was found in sizes heavier than 0.130 in., but was rather common in all thinner sheet, including 0.065 in., the smallest size examined. This grain-growth was moderate in most cases, the grain-size usually being between 0.08 and 0.12 mm. diameter. In some instances, however, a more coarsely grained structure was noted, occasionally as large as 0.40 mm. diameter, usually in the heavier sizes. Sheet is, of course, subject to rapid cooling during the rolling operation, and the presence of coarse grains in the finished material is probably due to the temperature falling within the critical range before rolling is completed, grain-growth occurring during cooling in the stock pile or on annealing. No grain-growth was observed in the heavier materials such as hot-rolled rod, plate, or sheet bar, either after rolling or after annealing within the critical range. Further annealing within the critical range seemed to have no effect on the grain-size of the sheet investigated.

The grain-size noted in cold-rolled annealed sheet varied considerably, but where grain-growth was found, the size was generally coarser than in hot-rolled sheet. Grain-growth occurred in all sizes down to and including 0.040 in., the lightest gauge examined. Grains 0.50 mm. in diameter were noted occasionally.

In many cases where sheet is used for such operations as pressing, a considerable increase in the number of operations becomes necessary when the material is coarse-grained; frequently the grain-size may be so large that the steel will not endure even light operations. In such cases the material can be made available for use by annealing at about 790° C. (1,450° F.); or in some cases a temperature just above 900° C. (1,650° F.) may be required. When the operations have been laid out according to the requirements of normal metal, the adjustment required to handle the coarse-grained material may be the cause of considerable difficulty in production.

There is no convenient method by which the condition of sheet can be determined absolutely. Microscopical examination, together with a tensile test, will indicate to a certain degree the condition of the metal and serve as a guide to its probable action in practice. These tests cannot be an infal-

libile guide, because the strain received may be too complex, or because the coarse structure may only occur here and there throughout the metal in certain areas that may or may not be located by the tests. Moderately coarse-grained sheet that gives perfect satisfaction in one case may be very unsatisfactory in another. In general, however, the tests mentioned will serve to indicate material of decidedly coarse grain and also material that has not been handled properly in rolling or annealing.

When methods by which grain-growth may be prevented or eliminated are known, the problem of prevention or elimination is narrowed to a proper selection of the method most applicable to the particular case. For example, with hot-rolled sheet prevention requires careful regulation of the finishing temperature, the reduction of area, and the annealing, if this operation be performed. When thin sheet is rolled, such regulation is exceedingly difficult. With cold-rolled sheet grain-growth can be eliminated by the use of heavy reductions, but here again other difficulties arise. Surface irregularities in the hot-rolled sheet and the difficulty of measuring exactly the gauge of large thin sheets makes an absolute determination of the reduction exceedingly difficult. Furthermore, a coarsely grained structure may have been introduced in the hot-rolling. From these considerations it can readily be seen that while grain-growth may be prevented by the use of heavy reductions the application of this method is not always commercially practicable.

Grain-growth in sheet may be eliminated by annealing the hot-rolled sheet at a temperature somewhat above 900°C . ($1,650^{\circ}\text{F}$.), and if the sheet is then cold-rolled the temperature of the subsequent annealing should be kept below 650°C . ($1,200^{\circ}\text{F}$.). Sheet treated in this manner will be somewhat stiffer than the ordinary annealed cold-rolled sheet, but can be strained to a considerable degree before annealing becomes necessary. The difficulties in the annealing of sheet at the high temperature are obvious, but many of these may be eliminated by the use of box annealing. That this method is commercially practicable is shown by the fact that sheet treated in this manner is now furnished in the States, and gives excellent satisfaction in some decidedly difficult pressing operations. This sheet is box-annealed after hot-rolling at a temperature somewhat above 900°C . ($1,650^{\circ}\text{F}$.), is then cold-rolled and annealed just below 650°C . ($1,200^{\circ}\text{F}$.). As stated, sheet treated in this manner seems to be somewhat stiff, especially so when compared with coarse-grained sheet, which is almost always extremely pliable, but when tested in pressing operations excellent results were obtained, especially in the more difficult deep-drawing operations. The use of this material permitted the elimination of many of the annealing operations which had been found necessary with the material usually employed. In many cases the increased cost of sheet annealed to remove coarse crystallization may be more than balanced by the elimination of much of the annealing usually required between operations and also by the increase in production obtained.

In cold-rolled strip steel, where the gauge can be determined accurately and close control of the rolling is usually possible, grain-growth can be prevented by the use of reductions of area above 25 to 30 per cent. This ease of control and the general use of heavy reduction probably accounts in some measure for the superiority of strip steel over sheet in pressing operations.

Tube.—Low-carbon steel tube is, of course, subject to grain-growth under the same conditions as other low-carbon steel materials. In this investigation, however, no extreme grain-growth was found, although a certain

amount was found in practically all the samples examined. The grain-size was usually not over 0.15 mm. diameter and a temperature of 900° C. (1,650° F.) was required in order to refine the structure.

Cold Pressings.—In certain pressing operations grain-growth may readily occur, causing serious difficulty in the process of manufacture or in service. Where steel 0.20 per cent. or higher is used, grain-growth of a troublesome nature will rarely be found, but in many cases the use of this material is out of the question and a lower carbon steel is required, in which grain-growth can readily be produced. The occurrence of this grain-growth in pressings is dependent upon the nature of the operation and the annealing temperature. The annealing of pressings is a process that is frequently looked upon as requiring only elementary temperature control, the only consideration being that the metal reach a temperature high enough to remove the effect of cold work. The usual tendency is to raise the temperature to a point high enough to ensure proper softening of the metal, the temperature frequently reaching the critical range within which grain-growth occurs. In many pressing operations the amount of permanent deformation is relatively slight, and in such cases improper annealing may cause extensive grain-growth. Control of the annealing temperature is of the utmost importance in these cases. The selection of the proper annealing temperature depends to some extent upon the nature of the operation and the condition of the metal. Although annealing above 900° C. (1,650° F.) or below 650° C. (1,200° F.) will prevent grain-growth, the use of these temperatures is not always feasible. Annealing just below 690° C. (1,275° F.) will usually produce grain-growth so slight that little trouble will occur in further operations. Such annealing will remove practically all the effect of cold work. In a few cases somewhat higher annealing temperatures are required, as, for instance, after certain upsetting operations (7) which require temperatures somewhat above the critical point at 690° C., and after a few pressing operations of a similar nature. In such cases, and also when it is necessary to refine a coarse-grained structure existing in the metal, the annealing temperature should be somewhat above the critical point at about 780° C. (1,440° F.), or, if the partial refining occurring at this temperature is not sufficient to permit further operations, it should be raised above the critical point at about 900° C. (1,650° F.).

Grain-growth of any extent can occur only when the strain received has been comparatively light, and control of this factor may prevent its occurrence. Increase in the extent or number of operations before annealing may often permit the use of almost any normal annealing temperature. Very often, however, the effect of the operation cannot be foretold, and occasionally some variation from normal conditions may occur, as, for instance, in the setting of the die or punch, which will introduce comparatively light strains into some part of the pressing where such strains would be entirely unexpected under normal conditions. Furthermore, there are many operations which must necessarily be very light, and where annealing is required, its proper regulation becomes essential. As it is in the earlier operations that grain-growth usually occurs, making further work on the material impossible until it has been properly annealed, only a comparatively small proportion of the product will ordinarily find its way into use in a dangerously coarse-grained condition after ordinary pressing operations. In some cases, however, the presence of coarse crystallization may not be detected in the manufacturing operations, and defective material may find its way into service. The cause of the trouble that may occur in many such cases is frequently obscure, as, for instance, in the occurrence of cracks in the blanked edges of pressings

and around punched holes. In these cases in particular the cause may be traced to the pressure of the cutting edge in blanking or punching, subsequent annealing producing a moderately coarse-grained condition in a narrow layer following the line of pressure. Its presence may not be detected in the manufacturing operations, or perhaps the annealing is a final operation, so that no trouble develops until the pressing is placed in service. After a short time cracks appear along the edge or around punched holes and extend rapidly into the section. In a general way this condition has been observed by manufacturers of pressings, who occasionally find it necessary to grind the edges of certain pressings, in order to continue operations without the development of cracks. In service slight bending moments at the edges of pressings of this nature will cause the development of cracks.

Pressings which are to be carbonized and hardened should be heated to above 900°C . ($1,650^{\circ}\text{F}$.) during the carbonizing process, to prevent or remove any coarse crystallization. Distinction should be made here, of course, between the grain-growth occurring through a pressing operation and subsequent annealing and the grain-growth which may be developed through the use of high temperatures in the carbonizing process.

General Methods of Prevention and Cure.

Many operations in the manufacture of low-carbon steel materials by means of cold work, especially in cold-pressing, are of such a nature that no annealing is required, and when eliminated no grain-growth can occur. In some cases, by slight changes in the methods of manufacture, annealing can be rendered unnecessary. When annealing is essential, the temperature must be carefully regulated and controlled. These considerations must be borne in mind by the user as well as the maker, for it may become necessary to apply further heat treatment to some material before it is put in service, and improper treatment may leave the material in a dangerous condition.

Where grain-growth has occurred and refining becomes necessary, heating above 900°C . ($1,650^{\circ}\text{F}$.) will bring about a complete refining of the grain. If the scale produced at this high temperature should be troublesome, the material may be quenched in water and subsequently annealed at 540° to 675°C . ($1,000^{\circ}$ to $1,250^{\circ}\text{F}$.) if necessary. A little concentrated hydrochloric acid thrown into the furnace at the start will permit ready removal of the scale. In some cases annealing at 790°C . ($1,455^{\circ}\text{F}$.) will produce a grain refinement sufficient to prevent further trouble.

Where annealing is necessary to remove the hardening effects of permanent deformation a temperature just below 690°C . ($1,200^{\circ}\text{F}$.) will usually give satisfactory results. In some cases a temperature of about 790°C . ($1,455^{\circ}\text{F}$.) may be required, and occasionally 900°C . ($1,650^{\circ}\text{F}$.) will be required. The choice of the annealing temperature depends upon the conditions existing in each case.

To summarize the foregoing, it may be stated that grain-growth in cold-worked low-carbon steel can be avoided by the application of comparatively heavy work to the metal before annealing, or by proper selection and control of the annealing temperature, according to the working conditions. If the metal is not annealed after the cold work no grain-growth can occur.

CONCLUSIONS.

1. Grain-growth in low-carbon steel will be produced by permanent deformation of the metal within certain limits, followed by annealing within certain temperature ranges.

2. The greater the amount of strain within these deformation limits, the smaller will be the grain-size produced by annealing.

3. The limits of the annealing range within which grain-growth due to permanent deformation will be produced are 650° and 900° C.

4. When the strain is less than a certain or "critical" amount, the annealing range within which grain-growth can occur seems to be limited by the thermal critical points at about 690° and 780° C.

5. The most practical standard by which to measure the permanent deformation, or strain beyond the elastic limit, seems to be the reduction of area. Experiments based upon measurements with this as a standard show that no grain-growth occurs following a reduction of area of less than about 7 per cent. or more than about 25 to 30 per cent. The "critical" strain mentioned seems to be marked by a reduction of area of about 9 per cent.

6. The refining action taking place at about 780° C. is a further indication of the presence of a thermal critical point at this temperature.

7. The presence of carbon causes a suppression of grain-growth, an effect which, while negligible when the carbon content is low, is very pronounced when the steel contains 0.15 per cent. or more. No noticeable grain-growth was found to occur in steels which were uniformly above 0.18 per cent in carbon content.

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NOTE.—A very complete bibliography of the subject of the deformation of iron will be found in Chappell's article.