some cases when part of the rolling from bloom to rail has been done, and when the metal in the intermediate stage of "billet" is reheated slightly, the part which is to form the head is purposely kept cooler than the rest by keeping the billet as it were on its head, *i. e.*, by putting the head part down in contact with the furnace bottom, while the part which is to form the flange lies uppermost and is fully exposed to the heat. Again, during the rolling, the part which is to form the head may be specially cooled by strong jets of cold water.

In particular the Kennedy-Morrison process* interrupts the rolling before the last pass, so as to allow the rail to cool and thus to give it a lower finishing temperature.

For welding, the two pieces which are to join are in general so shaped beforehand as to be much thicker at the point of junction than the finished and welded piece is to be. Hence, after welding proper, *i. e.*, after the first few blows which cause the two pieces to cohere firmly, the smith continues hammering so as to reduce the local thickness here to that aimed at in the finished piece, and this hammering is prolonged until the temperature has sunk to a harmlessly low point. The ultimate object of all this procedure is to give the metal at and about the weld, which has perforce been very highly heated so as to permit welding, a relatively fine grain and its attendant good qualities through having the finishing temperature low. The object, in short, is to permit this "mechanical" or "hammer" refining of the necessarily overheated parts.

We are only just beginning to accumulate data as to the therapeutic effect of mechanical refining. It is hardly to be supposed that, in rail-rolling, if all the passes except the last take place at a very high temperature, and that then the last pass only is at a proper temperature, this last pass will cure completely and surely the injury done by the previous high heating, especially if the amount of mechanical work, *i. e.*, the reduction of cross-section, in this last pass is very slight, as is almost necessarily the case. Thus, if we compare the grain-size of Fig. 76a with that of Fig. 79a, we see at once that the grain of the piece rolled at 963°, after slowly cooling from 1394° (*A*, Fig. 79a), is very much coarser than that of the piece (*C*, Fig. 76a), which was simply

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* *The Iron Age*, LXVI, Dec. 20, 1900, pp. 16-18.

heated at 966° and then cooled slowly. Certainly, the degree of mechanical refining here done, while it has reduced the grain-size, has by no means brought it down to the size corresponding to this same temperature as T^{max}. In other words, the grain-size for a given temperature taken as T^{max} is much finer here than that corresponding to the same temperature taken as finishing temperature. Whether with greater reduction in the rolls the grain-size for given finishing temperature would be nearly the same as that corresponding to the same temperature as T^{max}, remains to be seen.

219 *B*. FURTHER CONSIDERATION OF THE INFLUENCE OF T^{max} ON THE PHYSICAL PROPERTIES. — It has been pointed out already that, while the coarseness due to extreme overheating is accompanied by very great injury, and while it is true as a rough generalization that the quality of a given variety of steel is the better for most purposes the finer its grain, yet this is true only when we compare grains differing much in fineness, *e. g.*, very coarse grain with very fine grain. When we come to consider the properties corresponding to different sizes of grain all of which are fine, and all therefore due either to a low T^{max} or to low finishing temperature, we have to qualify this law very greatly; and we find that in certain respects a very low T^{max} or a very low finishing temperature may be much less desirable than one slightly higher.

It would be well if we could proceed at once to study the relation between grain-size and physical properties of direct importance to the engineer, tensile strength, elastic limit and ductility; but unfortunately we have little direct evidence bearing on this relation. We therefore turn to the relation between T^{max} and finishing temperature on one hand, and these physical properties on the other. Even here our knowledge is as yet extremely fragmentary; but to facilitate the study of such data as are at hand I have plotted in Figs. 79b, 79c, and 79d the results obtained by Ball and by the Westinghouse Machine Co., together with those of several investigations in my own laboratory. Further I give in Table 12 some later results which I have reached while this work was in press, with the assistance of Mr. I. C. Bull, who performed the manipulations, and in Table 13 the results obtained by Dr. Wm. Campbell in my laboratory.

Looking at these results in a general way, we note first that they verify the generalization made long ago, that the influence of

TABLE 12.—*Influence of the Temperature from which Steel is Cooled Slowly upon its Physical Properties.*

SLOWLY COOLED AFTER HEATING TO	TENSILE STRENGTH POUNDS PER SQUARE INCH	ELASTIC LIMIT POUNDS PER SQUARE INCH	ELONGATION PER CENT IN 8 INCHES	REDUCTION OF AREA PER CENT
Steel No. 164	Carbon 0.035	(Si .093		P. 0.093)
750° C.	28,353	19,948	28.00	79.72
1100° C.	28,657	18,130	30.00	78.37
1300° C.	28,529	12,142	35.00	77.01
1400° C.	30,064	11,483	13.25	76.46
Steel No. 39	Carbon = 0.22	(Mn = .44	P = .008	S = .018)
750° C.	52,608	30,715	15.25	68.54
1100° C.	52,374	19,242	15.00	61.84
1300° C.	52,241	19,159	19.25	58.77
1400° C.	50,313	12,880	—	56.62
Steel No. 193	Carbon = 0.70	(Si = .141 Mn = .068	P = .012	S = .019)
750° C.	82,660	40,062	12.00	25.42
1100° C.	92,342	59,363	13.12	20.35
1300° C.	48,921	29,247	1.12	17.22
1400° C.	41,327	33,082	1.25	15.10
Steel No. 46	Carbon = 0.92	(Si = .124 Mn = .240	P = .014	S = .025)
750° C.	81,087	34,710	13.50	43.66
1100° C.	109,586	39,226	7.50	14.14
1300° C.	106,913	33,992	4.50	7.88
1400° C.	64,189	42,008	0.50	5.13
Steel No. 192	Carbon = 1.04	(Mn = .12	P = .012	S = .017)
750° C.	83,046	51,400	13.75	53.84
1100° C.	107,814	65,926	10.37	22.17
1300° C.	88,376	48,643	3.37	16.23
1400° C.	46,055	32,051	0.87	11.24

Four test pieces were cut from each of five lots of steel. They were then heated extremely slowly to the temperatures indicated. In each heating five test pieces, *i.e.*, one from each of the different lots of steel, were set compactly side by side within a long narrow muffle, with the thermo-couple of a Le Chatelier pyrometer in their middle. The muffle closed at each end, was completely enclosed in a special cylindrical gas forge, also closed at each end, and in such a way that both ends of the muffle were within the flame of the forge. The temperature was then raised very slowly, especially towards the end of the heating, until the desired temperature was reached. The steel was then allowed to cool slowly within the muffle. The manipulations were performed by Mr. I. C. Bull under the author's directions.

thermal treatment increases rapidly with the carbon-content (note that the lowest-carbon steel, with only 0.035 per cent of that element, is practically unchanged as regards tensile strength and reduction of area, even by heating to 1400°).

TABLE 13.—*Influence of Finishing Temperature upon the Physical Properties of Steel of 0.50 per cent of Carbon. W. Campbell.*

BAR NO.	SERIES NO.	BARS COOLED FROM	ROLLING TEMPERATURE CENTIGRADE	TENSILE PROPERTIES			
				Tensile Strength Pounds per square inch	Elastic Limit Pounds per square inch	Elongation Per Cent in 8 inches	Contraction of Area Per Cent
A	—	1390°	Not rolled	102,000	60,700	3.4	5.5
1	1	1399° C.	874°	119,700 123,000	110,200	—	16.6
2	"	"	820°	109,500	96,500	9.	26.3
3	"	"	749°	115,400	77,000	7.	20.5
4	"	"	Ar 2-3 is 700° ± 686°	111,600	79,200	5.25	8.3
1	2	1394° C.	963°	126,800	86,050	9.6	28.0
2	"	"	909°	127,400 128,300	86,800	10.25	27.0
3	"	"	837°	128,400	84,400	10.25	29.7
4	"	"	809°	126,000	84,700	10.75	33.0
5	"	"	781°	126,500	87,700	10.	33.4
6	"	"	755°	130,000	95,100	8.	39.0
7	"	"	724°	124,200	89,400	9.4	41.3
			Ar 2-3 is 700° ±				
8	"	"	695°	129,100	94,700	9.75	29.6
9	"	"	669°	130,200	98,050	8.75	27.3

ELASTIC LIMIT. — When steel is simply heated, as in annealing, to a high temperature, and then cooled slowly without undergoing mechanical work, the elastic limit varies in a most important way with the temperature from which the slow cooling occurs. As this temperature is progressively raised in a series of like samples, the elastic limit reaches a minimum at about Ac_1 or say 710° to 730° C., then rises, usually sharply, to a maximum at a temperature usually but little higher, say between 750° and 850°, and then again decreases progressively. Turning to Fig. 79b, we find this true in four of the five series which give data covering this matter, and in the fifth we find the same law, with the exception that the depression at the minimum is much slighter than in the others (W. M^{c}. C^{o}.) A. Further, in the sixth series (W. M^{c}. C^{o}.) F., the data show a sharp maximum which corresponds very closely with that of the other investigations; and, while they do not positively prove the existence of the minimum at 750°, yet they certainly contain no suggestion that this minimum is here lacking. This agreement, which was wholly unlooked for, in these different series of results by three different investigators, goes far towards establishing this law.

Again, in Table 13, we find that, as the finishing temperature of a series of bars is progressively raised, the elastic limit behaves in a somewhat similar way, at least as regards reaching a distinct maximum decidedly above Ar$_{2-3}$. In the second series in which alone the data are full enough to detect a minimum, one is found, though not indeed a very marked one, at 724° C., *i. e.*, in the same temperature range as the minimum found in the Fig. 79b. I do not like to insist on this latter point because the evidence is so scanty. But at least we may say this, that there is nothing in the finishing temperature data inconsistent with the teachings of the T$^{\max}$ data. Indeed, we can hardly expect that like variations in finishing temperature and in T$^{\max}$ are to have exactly parallel effects.

We may therefore provisionally formulate law [10] as follows:

[10] As the temperature from which the slow undisturbed cooling of medium-carbon steel occurs, is progressively raised, the elastic limit of the cold steel falls to a minimum as this temperature reaches about 700° (Ac$_1$?), then it rises sharply to a maximum as the temperature rises slightly higher (say to 750° or 800° C.), and then again decreases progressively.

From the data here given we may also formulate law [11]:

[11] In general the slower the cooling the lower is the elastic limit.

It is wholly in accordance with law [10] that Mr. P. H. Dudley finds that rail steel with extremely fine structure (say 10,000 granulations to the square inch), though it is ductile and resists

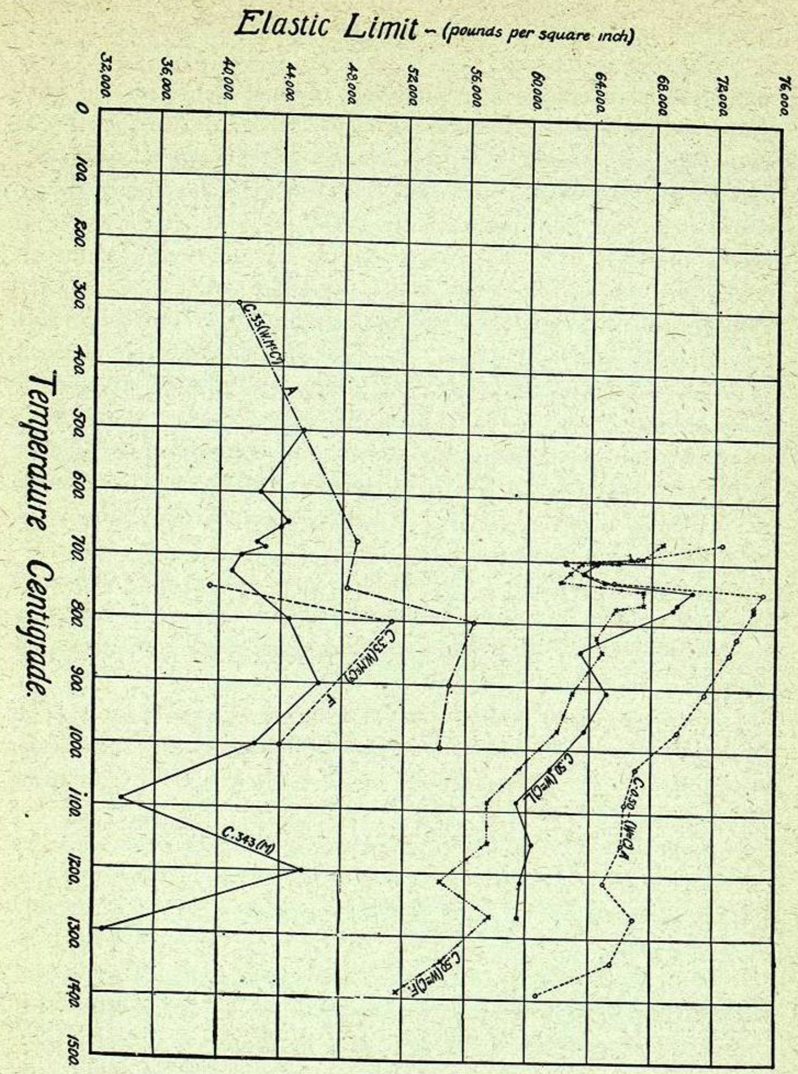

Fig. 79b. Influence of the Temperature from which Steel is Cooled Slowly, upon its Elastic Limit.

Note and Legend to Figs. 79b, 79c and 79d.

NOTE. — In each case the steel is supposed to have been heated to the temperature indicated, and then cooled slowly without undergoing any mechanical work.

Legend: C .33, C .50, *etc.* = 0.33, 0.50, *etc.*, per cent Carbon.
(Au.) = The Author, *Trans. Am. Inst. Min. Eng.*, XXIII, pp. 527, 529, 531 and 532.
(Ba.) = E. J. Ball, *Journ. Iron and Steel Inst.*, 1890, I, Plate VI, Fig. III.
(B.) or (Bd.) = R. H. Bradford, from unpublished results reached in the Author's Laboratory.
(Wm. C.) = William Campbell, from results, to be published, reached in the Author's Laboratory.
(M.) = R. G. Morse, *Trans. Am. Inst. Min. Eng.*, XXIX, p. 745.
(W. M^{c}. C^{o}.) = Westinghouse Mach. Co., *The Metallographist*, VI, April 1903, Frontispiece.
A = cooled in air. F = cooled in furnace. L = cooled in lime.

wear well, yet has too low an elastic limit. A rail should have three chief properties; ductility to insure power to resist the shock of the driving wheels, in order that it may not break; resistance to abrasion, that it may not wear out; and high limit of elasticity, that it may not take permanent set and be bent into a series of waves between its supporting ties, by the enormous pressures which the wheels of to-day throw upon it. According to Mr. Dudley's observations, and his opportunities and powers of observation are of the very best, rail steel of such composition as he likes (carbon 0.55 to 0.60 per cent, silicon 0.10 to 0.15, manganese 1.20, sulphur under 0.06, phosphorus under 0.06), should have somewhere between 5000 and 10,000 granulations to the square inch. If it has fewer, *i. e.*, if it is coarser grained, it is likely to be too brittle; if it has more, *i. e.*, if it is fine grained while it may be more ductile, yet its elastic limit will be too low.*

Our natural inference is that the low elastic limit which he finds in rails with extremely fine grain is due to a finishing temperature below that which, according to Fig. 79b, gives the maximum limit of elasticity.

This case is of interest as showing how important it is to check by large scale experiments and industrial tests the teachings of our laboratory investigations, and how each throws light upon the results of the other.

ELONGATION. — With 0.34 per cent of carbon or less we cannot readily detect any important and regular effect of the variations in the temperature from which slow cooling occurs as regards the elongation.

With 0.50 per cent of carbon (Wm. Campbell's data), as the temperature from which slow cooling occurs is progressively raised, the elongation of the cold steel decreases moderately until this temperature reaches about 1200° or 1300°; and the elongation decreases rapidly with farther rise of this temperature. The decrease is not very regular, and indeed for short distances turns into a decided increase; but this seems referable rather to individual peculiarities or observational errors than to any general law. I have here in mind particularly the fact that, for given ductility or true elongation, the observed elongation may vary very con-

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* *The Metallographist*, VI, p. 111, and private communication, May 12, 1903.

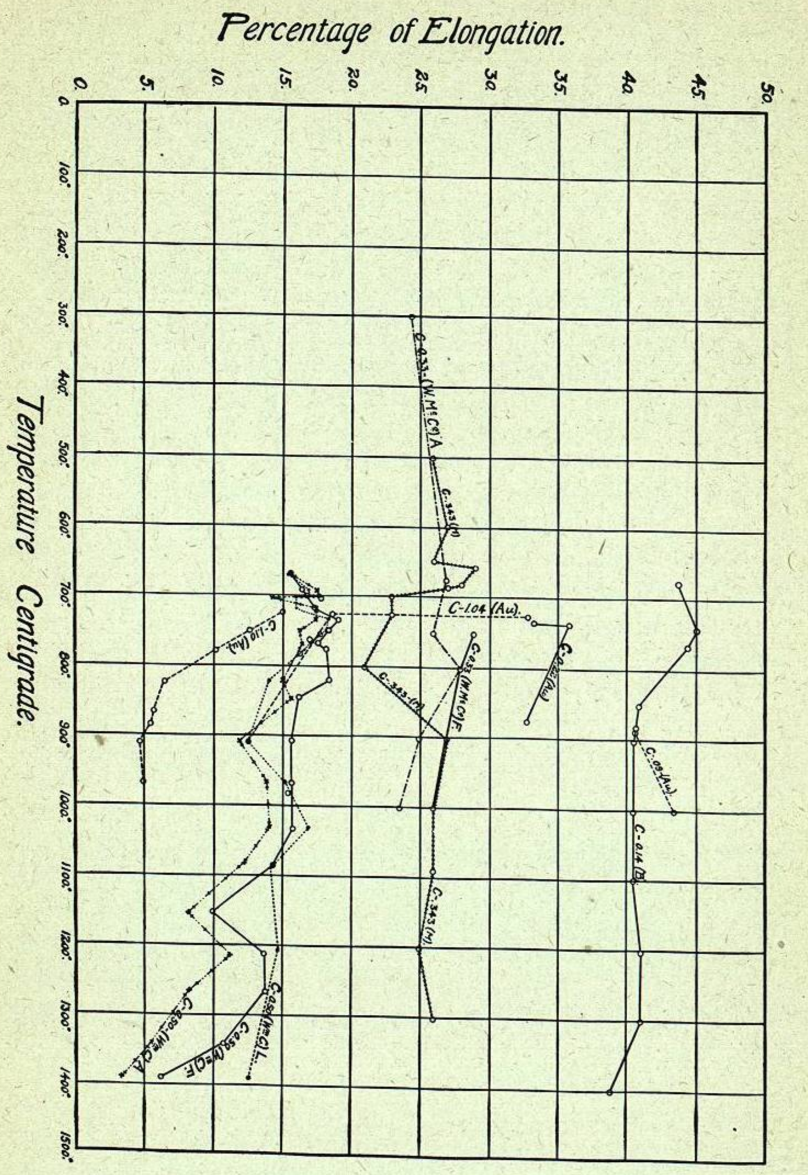

Fig. 79c. Influence of the Temperature from which Steel is Cooled Slowly upon its Ductility.

(See Note and Legend, p. 271.)

siderably with the position in the length of the test piece where rupture occurs.

With 0.70 per cent of carbon (Table 12) the indications are much the same.

With hyper-eutectoid steel (4 cases by the author), the elongation falls off continuously and markedly with every rise of temperature from which slow cooling occurs. In two cases this decrease is much sharper about Ac_1 than at higher temperatures; the data in the other two cases do not indicate clearly whether the decrease varies in this way.

To sum this up, the effect of raising the temperature from which slow cooling occurs is, in general, to lessen the ductility as measured by the final elongation of the test pieces cut from the cold steel. This effect increases rapidly with the carbon-content, being relatively slight in case of steel of 0.34 per cent of carbon or less, but very great in case of hyper-eutectoid steel. There are indications of a general law that the decrease of elongation is especially marked as the temperature rises past Ac_1, and again very marked as the temperature rises above 1300°.

This is in general accord with Prof. Sauveur's* early determination of the relation between the ductility and the grain-size of rail steel. He found that the elongation decreased as the grain-size increased; whence we infer that it decreased as the finishing temperature increased, or in other words that the influence of finishing temperature is like in kind to that of T^{max}.

TENSILE STRENGTH. — In case of steel with less than 0.33 per cent of carbon the temperature from which slow cooling occurs appears to have little influence on the tensile strength, as far as the data here given show; but it is the general belief that if that temperature approaches the melting-point (probably if it enters region II of Fig. 68), the tensile strength decreases. The data here given do not cover this high range of temperature for such low-carbon steel.

In case of higher-carbon steel, the tensile strength at first increases as the temperature from which slow cooling occurs rises above Ac_1 to 800°, or even in cases to 900° or 1000°. Then, after varying somewhat, it falls off very abruptly in case of steel of 0.50 per cent of carbon, when that temperature approaches 1400° C.

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* *Trans. Am. Institute Mining Engineers*, XXII, p. 556, 1893.

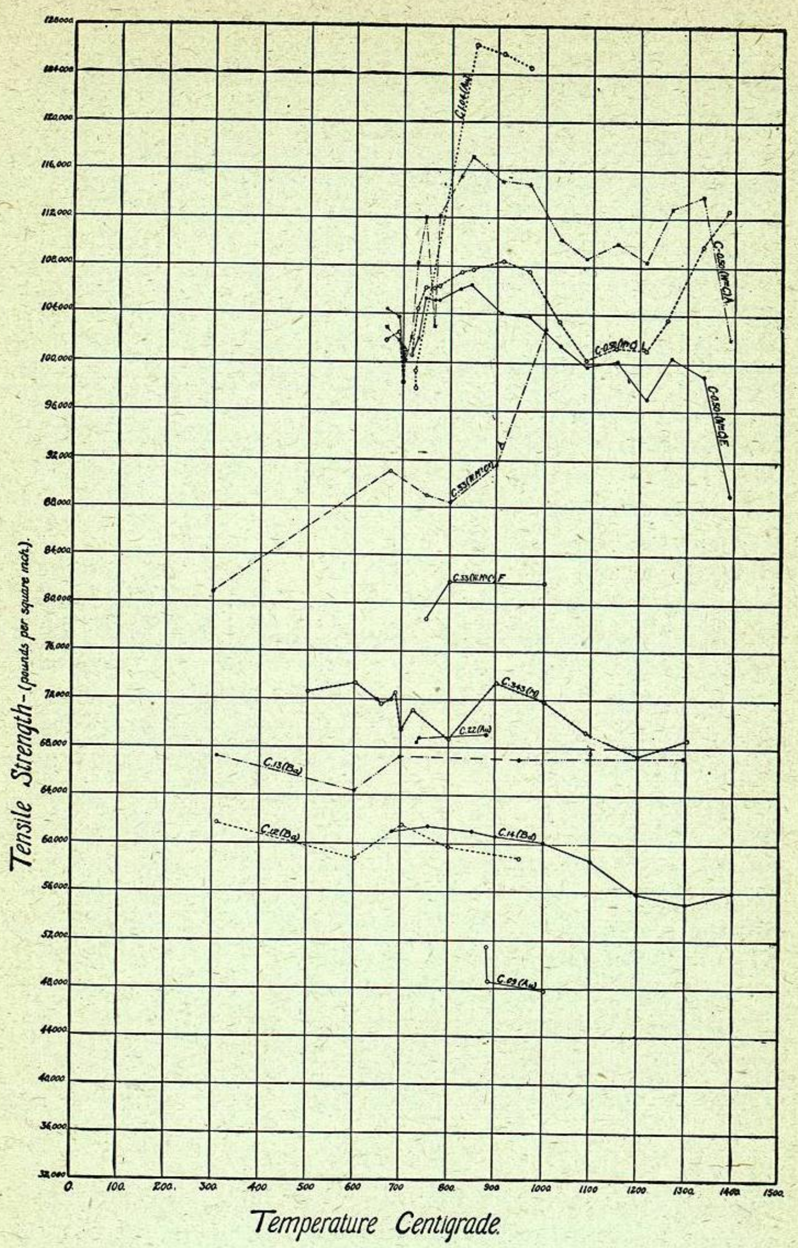

Fig. 79d. Influence of the Temperature from which Steel is Cooled Slowly, upon its Tensile Strength.

(See Note and Legend, p. 271.)