THERMAL EXPANSION OF A FEW STEELS

By Wilmer Souder and Peter Hidnert

ABSTRACT

Thermal expansion data are given on 28 specimens of iron and steel. Most of the specimens were heated above 900° C. Tables and curves are used to summarize the results. The tests were made by direct measurements of the length changes and not relative to some other substance or element. The observations were made without disturbing the furnace or specimen and therefore give correct relative values for all temperature intervals.

Variations in length changes, contraction and expansion reversals while passing through the critical regions, and similar changes are compared and discussed.

An attempt is made to throw some light on the magnitude of the tendency toward warping or surface cracking as related to the rate of cooling and width of critical regions.

Expansion coefficients are tabulated for the various alloys and for various temperature intervals.

Data on one specimen of vacuum electrolytic iron and one of gray cast iron are recorded. The length changes incident to the drawing of a sample of hardened steel are shown in a curve.

A brief review of some of the previous work on expansion is included.

CONTENTS

1. INTRODUCTION

The anomalous expansion of iron and certain steels when heated over the range 600 to 1000° C has been known for a number of years. The structural changes taking place at or near these points of nonuniform expansion have been given considerable attention within the last decade. In addition to the irregularities in expansion, which are influenced by these changes, there are numerous other physical properties which are modified during the passage through the above temperature range. Among the effects which have been used to more accurately chart this region are: Changes in electrical, magnetic, elastic, and thermal properties, changes in microstructure, hardness, and rate of expansion.

The present paper presents additional data on the last-named property, and while the emphasis will not be placed on the structural or molecular phases often accompanying the variations in expansivity, it is felt that the data may be of sufficient accuracy to warrant their use for certain parts of such study should one care to make such use of them. The results represent direct measurement of expansion on a number of selected specimens and are perhaps above the average in accuracy for direct, continuous measurements of thermal expansion.

The principles of hardening and heat treatments of steel are dependent to some degree upon the proper handling while within the above range. Our comments on the dimensional changes will bear upon the physical effects which may be expected to accompany these dimensional irregularities. The shrinkage, warping, surface cracking, and usual lack of highest accuracy of dimensions met in heat-treated work render data on expansion and contraction worthy of careful consideration.

2. PREVIOUS WORK

Svedelius, Le Chatelier, Charpy and Grenet, Guillaume, Driesen, Honda, and other investigators have done work on the thermal expansion of iron and steel. Since a satisfactory review of their work would require considerable space in comparison with that of the other sections of this paper, it was decided to point out only a few of the results or conclusions of some of the previous observers. For additional information, reference should be made to the original papers.

Charpy and Grenet [1] found that, if small samples of medium steels (0.6 to 1 per cent C) and of high-carbon steels were heated above 900° C and quenched in water, the expansion curves of the former show abrupt contraction of about 1 per cent between 250 and 350° C, and the curves of the high-carbon steels indicate two contractions, one at about 150 and the other at 300° C.

In a later paper [2] these authors compare results obtained in the critical regions of steels by three different methods. The following tables show the comparative values:

[1] Charpy and Grenet, C. R., 136, pp. 92–94; Jan. 12, 1903.

[2] Charpy and Grenet, C. R., 139, pp. 567–568; Oct. 10, 1904.

TABLE 1.—Comparison of Electrical Resistance and Dilatation Methods (Charpy and Grenet)

Carbon content	Electrical resistance method		Dilatation method	
	Transformation begins	Transformation ends	Contraction begins	Contraction ends
	°C	°C	°C	°C
0.82 per cent	730	760	735	745
1.06 per cent	730	760	740	750
1.15 per cent	739	739	735	740
1.38 per cent	750	750	735	755

TABLE 2.—Comparison of Thermoelectric and Dilatation Methods (Charpy and Grenet)

Carbon content	Thermoelectric method		Dilatation method	
	Maximum of $\frac{dE}{dt}$	Minimum of $\frac{dE}{dt}$	Contraction begins	Contraction ends
	°C	°C	°C	°C
0.28 per cent	720	840	720	820
0.62 per cent	700	760	743	760
0.92 per cent	700	800	737	760
1.14 per cent	708	780	747	760
1.30 per cent	680	740	725	740

Charpy and Cornu[3] found that more than 1.3 per cent Si in low-carbon steels (0.1 per cent C, 0.3 Mn), caused the expansion curve to be almost rectilinear from 0 to 900° C, without an indication of a critical region. However, for an alloy containing 0.35 per cent C and 0.8 per cent Mn, it required 4.5 per cent Si to show a similar phenomenon.

Driesen[4] states that above the critical region, the coefficients of expansion of carbon steels are practically constant for samples containing less than 0.85 per cent C. This conclusion is in agreement with the results of Charpy and Grenet.[5] The carbon steel containing 0.33 per cent C showed the maximum change of length during the critical region. Honda[6] gives data which are in close agreement with this result, for he found that a steel containing 0.31 per cent C indicated the maximum contraction in the trans-

[3] Charpy and Cornu, C. R., 156, pp. 1240–1243; Apr. 21, 1913.

[4] Driesen, Ferrum, 11, pp. 129–138, Feb., and pp. 161–169, Mar., 1914; Rev. de Mét., 14, pp. 683–706, Sept.–Oct., 1917.

[5] Charpy and Grenet, C. R., 134, p. 540; 1902.

[6] Honda, Tôhoku Univ., Sci. Reports, 6, pp. 203–212, Nov., 1917.

formation region. Driesen also found that steels containing more than 0.65 per cent carbon and quenched from above 900° C contract on reheating to about 300° C, and with steels containing more than 1 per cent carbon a similar phenomenon is also observed at 100 to 150° C.

Ōkôchi and Satô [7] determined the growth of gray cast iron on repeated heatings. They found that permanent growth is never produced below the transformation temperature. They state the rapid expansion from about 650° C to near the transformation point in the first heating is due to the separation of free carbon from cementite. There are two periods of growth: (1) During the transformation, and (2) at temperatures above the transformation.

Benedicks and others have used certain modifications of the thermal expansive relations to more accurately define transformations in structure, etc. However, since these tests are, in general, only differential tests of expansivity, no claims being made for the absolute values of thermal expansion, or since their application has been limited to metallurgical considerations, it is not within the province of this review to discuss their results.

In many instances we have been prevented from making more detailed comparisons of this work with that of other investigators because of the more complex composition of these steels. While the agreement on carbon content, for example, may be good, the included manganese, vanadium, or chromium may have introduced an unknown effect. These steels were selected with the idea of securing representative specimens rather than any special series of some one alloying element.

3. APPARATUS

The apparatus [8] of the Bureau's expansivity laboratory was used. The specimens were 30 cm in length and about 1 cm in diameter. The platinum-osmium position wires were placed in sharp V-notches cut near each end and at right angles to the axis of the specimens. In this manner the oxide which always formed did not influence the longitudinal separation of the vertical position wires. Attempts to gold plate the specimens or to use neutral gases in the furnace were not successful, due perhaps to the occluded gases which could not be displaced; hence the above method of setting the wires in notches was adopted and proved quite satisfactory.

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[7] Ōkôchi and Satô, Tokyo Univ. Coll. of Eng., J. 10, pp. 53-71, Feb., 1920.

[8] Described in B. S. Sci. Papers, No. 352.

4. RESULTS

This work (with one or two exceptions) deals with annealed alloys. The specimens were carried through the transformations at a slow rate of temperature change, usually less than 1 degree per minute. The length changes showed little, if any, lag for temperature variations. Intentional reversals in temperature gradient were accompanied by corresponding reversals in length changes and without a lag of more than 2 minutes. A further confirmation of the uniformity of temperature throughout the entire specimen is found in the sharp breaks in the expansion curves, indicating that practically all parts began the transformation at the same instant. This uniformity of temperature is more readily maintained at high temperatures than at lower temperatures because of the rapid increase in rate of transfer of radiant energy with increase of temperature.

In some instances the tests were disturbed before all data were taken, and in repeating the test only a few points were taken within the range of the previous test. These points usually agreed with the previous test, and in such cases the second run is shown in the curve as a dotted or broken line. (See Fig. 15.) Heating values are indicated by open center circles and cooling values by dark center circles. Where the observations were so numerous that these circles interfered with each other the curve has been omitted. The specimen was watched constantly to see that no smaller variations were overlooked. When the expansion or contraction appeared to be regular these intervening observations were not recorded, or if recorded were not used in the plots.

The cast-iron specimen S483 (Fig. 17) is included to show the rapid growth at high temperature. Additional work is being planned to cover this field more thoroughly. The specimen of hardened steel (Fig. 16) gives a graphical picture of the shrinkages accompanying the drawing process.

Little if any of the above work can be considered as new information. It is perhaps a further confirmation of the findings of other observers, many of which were using entirely different lines of attack. The results will indicate the accuracy and ease with which it is possible to investigate materials at higher temperatures by this method of thermal analysis. Doubtless much of the value of these data will be worked out by those more closely connected with the industrial applications of such.

The results of the expansion measurements are given by the curves of Figs. 2 to 22 and the data relating thereto are assembled

TABLE 3.—Results of Analyses and Measurements of the Samples

PART 1.—RESULTS OF CHEMICAL ANALYSES

Lab. No.	C	Mn	P	S	Si	Cr	V	Ni	Miscellaneous
S546	0.35	1.42	0.013	0.057	0.20	1.00	0.11	...	
S547	.49	1.21	.05	.050	.12	...	...	...	
S548	.41	.64	.052	.061	.086	...	...	...	
S549	.44	.57	.013	.033	.161	...	.14	...	
S550	.59	.92	.024	.033	.25	...	...	...	
S551	.35	.08	.010	.027	.110	1.17	.14	...	
S552	.36	.46	.011	.029	.09	.57	.12	...	
S553	.168	.01	.010	.026	.135	2.50	.39	3.94	
S554	.410	1.11	.053	.049	.115	...	...	2.00	
S555	.144	.10	.03	.035	.034	1.15	.21	...	Cu 1.85
S556	.252	.06	.012	.035	.007	...	...	...	
S557	.168	.08	.010	.029	.038	.92	.24	...	Mo .64
S558	.122	.05	.020	.040	.846	.85	.23	...	
S559	.326	.78	.014	.035	.094	...	...	3.59	
S560	.342	.28	.01	.043	.094	.82	.26	...	Cu 2.70
S561	.396	.25	.012	.023	.095	...	...	...	W 3.96
S562	.380	1.17	.055	.067	.10	...	...	.81	
S563	.388	1.21	.010	.043	1.04	...	...	3.67	
S564	.512	.42	.016	.021	1.45	...	...	...	W 1.58
S565	.30-.40	...	...	...	...	13.00	...	...	
S566	.418	.68	.012	.025	.23	...	...	...	
S507	.02	nil	nil	.007	.006	(Co, Cu, Ni, total 0.014)			
S482	1.28	.37	...	...	...	.19	...	...	
S504	.20	1.10	.05	.05	...	.5	...	.5	
S483	3.08	...	...	...	1.68	...	...	...	
S484	.14	...	...	...	...	...	...	34.52	
S457	.09	.19	...	...	3.70	1.76	.005–	.05–	
S614[a]	.85	1.00	<.02	...	.25	.50	...	...	W .45

PART 2.—AVERAGE COEFFICIENTS OF EXPANSION ON HEATING (TEMPERATURES INDICATED) $\times 10^6$

Lab. No.	25 to 100° C	100 to 200° C	200 to 300° C	300 to 400° C	400 to 500° C	500 to 600° C	600 to 700° C	25 to 300° C	300 to 600° C	25 to 600° C
S546	12.4	12.8	14.4	15.1	15.9	15.9	16.2	13.3	15.6	14.5
S547	11.3	12.2	14.2	16.3	17.7	15.4	16.7	12.7	16.5	14.7
S548	11.1	12.2	14.3	15.8	15.7	16.0	16.6	12.7	15.8	14.3
S549	11.2	12.4	14.3	15.4	16.4	16.5	16.8	12.7	16.1	14.5
S550	11.1	12.5	14.6	15.4	16.1	16.8	16.6	12.9	16.1	14.6
S551	11.0	12.3	14.8	15.6	15.9	16.5	16.2	12.9	16.0	14.5
S552	11.8	12.6	14.4	15.1	16.0	16.6	16.8	13.1	15.9	14.5
S553	10.8	11.7	13.5	14.0	14.5	14.4	...	12.1	14.3	13.3
S554	11.6	11.9	14.0	16.2	15.7	16.5	16.4	12.6	16.1	14.4
S555	11.2	12.6	13.8	15.6	15.6	16.0	16.7	12.7	15.7	14.3
S556	11.1	12.0	14.2	15.5	15.9	16.6	16.9	12.5	16.0	14.3
S557	11.3	11.8	13.9	15.3	15.7	16.6	16.1	12.5	15.9	14.2
S558	11.6	12.5	13.7	14.6	15.2	16.0	15.8	12.7	15.2	14.0
S559	10.9	11.5	13.6	15.2	15.1	15.7	...	12.1	15.3	13.8
S560	11.6	12.6	14.2	16.0	15.9	16.4	16.9	12.9	16.1	14.6
S561	11.1	12.0	14.0	15.1	15.7	16.4	16.5	12.5	15.7	14.2
S562	11.2	12.7	14.3	15.2	16.2	16.7	16.4	12.9	16.1	14.5
S563	11.6	12.0	13.2	14.2	15.2	15.6	...	12.3	15.0	13.7
S564	10.4	12.1	13.7	15.9	15.7	16.1	...	12.2	15.9	14.2
S565	10.0	10.6	12.0	12.6	13.5	13.9	13.7	11.0	13.3	12.2
S566	9.4	12.0	14.3	15.3	16.4	17.1	16.8	12.1	16.2	14.3
S507	12.0	13.0	14.5	15.3	15.9	16.8	17.4	13.3	15.9	14.7
S482	11.0	11.6	13.6	15.1	16.3	16.1	17.0	12.0	15.9	14.1
S504	12.3	12.9	14.2	15.9	16.2	16.5	16.8	13.2	16.5	14.9
S483[b]	8.4	11.7	14.2	15.6	14.3	Growing		11.6	Growing	
S484	3.7	8.4	14.1	16.6	18.4	18.8	19.1	9.2	18.2	13.6
S457	11.1	12.4	13.3	14.0	15.6	16.0	16.9	12.6	15.3	14.0

[a] Hardened from 850° C; scleroscope 60; shortened 1.2 mm per meter.

[b] Expansion values must be considered as approximate only, since the values doubtless contain a percentage of growth in addition to expansion.

TABLE 3—Continued

PART 3.—CRITICAL REGION DATA

Lab. No.	Heating: Temp. contraction began	Heating: Temp. contraction ended	Heating: Contraction	Heating: Average rate of heating	Cooling: Temp. expansion began	Cooling: Temp. expansion ended	Cooling: Expansion	Cooling: Average rate of cooling
	° C	° C	μ/m	° C/ minute	° C	° C	μ/m	° C/ minute
S546	742	792	1255	0.38	682	661	1475	0.49
S547	723	771	1495	.80	687	640	1540	....
S548	722	780	1440	.37	....	665	....	....
S549	735	790	1495	.71	746	675	1325	.79
S550	729	759	1605	.73	685	659	1590	.79
S551	759	806	1910	.57	769	717	1805	.69
S552	744	811	1535	.67	763	695	1605	.68
S553	711	790	860	.84	431	332	1515	.50
S554	730	817	740	.76	781	715	695	.93
S555	764	826	1135	.54	785	704	1415	.78
S556	734	823	1410	.82	806	732	90	.87
S557	774	858	700	1.55	839	757	795	2.35
S558	806	811	....	.53	....	....	....	.82
S559	688	742	1730	.90	621	542	1205	1.01
S560	738	794	1310	.50	746	685	1450	.68
S561	758	837	820	.65	817	738	1010	.67
S562	718	787	1300	.50	730	637	1200	.83
S563	694	730	970	.61	550	540	....	.56
S564	735	770	1580	.72	738	676	1335	.90
S565	864	886	605	.92	846	805	835	1.14
S566	725	768	1710	.83	721	665	1725	.75
S507	912	917	1310	.67	906	903	163	.50
S482	732	742	1000	.32	712	694	660	2.78
S504	722	833	1230	.36	747	648	1020	.89
S483	790	810	Indef.	.30	775	746	2120	.54
S484	None	None	None	....	....	....	....	....
S457	None	(Coeff. 800 to 900 = 17.7; 900 to 1000 = 18.9; 25 to 1000 = 15.3)						

PART 4.—EXPANSION DATA

Lab. No.	Average coefficient of expansion (× 10⁶) above critical region: Heating	Temp. range	Cooling	Temp. range	Coefficient on cooling 600 to 25° C	Increase in length at 25° C	Maximum difference in heating and cooling curves	Temp. of maximum difference
		° C		° C			μ/m	°C
S546	23.4	825–900	22.7	900–725	14.5 × 10⁻⁶	−1202	−1250	513–555
S547	....	....	22.7	900–700	14.6	− 462	− 630	485–515
S548	22.7	800–900	22.7	900–800	14.5	− 110	− 125	363–393
S549	22.8	800–900	22.8	900–800	14.4	− 82	− 145	505–525
S550	24.0	800–900	23.1	900–725	14.5	− 400	− 465	343–380
S551	24.1	825–900	22.8	900–800	14.3	− 270	− 355	585–613
S552	24.0	825–900	22.6	900–800	14.4	− 90	− 195	640
S553	....	....	22.3	900–550	10.7 (275–25°C)	− 680	....	290
S554	....	....	21.9	900–800	14.5	− 198	− 225	405–423
S555	....	....	22.0	900–805	14.2	+ 343	+ 380	85–150
S556	....	....	23.0	895–820	14.3	− 593	− 730	675
S557	....	....	....	....	13.9	+ 98	+ 160	180–225
S558	....	....	....	....	14.0	+ 346	+ 360	90–160
S559	22.2	800–900	22.8	900–700	13.1 (500–25°C)	− 727	− 875	515–525
S560	....	....	....	....	14.5	+ 335	+ 380	125–195
S561	....	....	....	....	14.1	+ 18	+ 110	182–223
S562	....	....	22.7	900–800	14.5	− 200	− 225	515–520
S563	22.6	800–900	21.1	900–600	10.9 (500–25°C)	− 920	−2080	525–530
S564	23.0	800–900	23.0	900–800	14.2	− 148	− 180	408–455
S565	....	....	....	....	12.1	− 63	− 100	570–615
S566	22.6	800–900	23.1	900–800	14.5	− 366	− 366	25
S507	23.4	905–945	23.4	917–945	13.3	− 120	−1500	912
S482	34	750–875	28.6	875–713	14.3	....	− 825	712
S504	23.4	833–950	21.6	950–760	14.8	− 430	− 510	600
S483	37	815–900	25	900–775	14.1	+9040	+9340	300
S484	....	....	....	....	13.6	....	....	....
S457	....	....	....	....	12.6	0	0	....

in Table 3. These results can be more readily interpreted by classifying them under the characteristics of the theoretical curve of Fig. 1. This curve represents the critical regions within which anomalous length changes occur. Most of the specimens followed the sequence of expansion as shown by the curve A, B, C, D, E, F, G of this figure. The length increments were usually quite regular up to point B, where they reversed sign and were recorded as contractions until point C was reached. From point C the expansion was usually greater than at any previous point. On cooling from D to E the contraction corresponded to the expansion on heating. At E the contraction ceased and an expansion was recorded until point F was approached. Below this point the contraction was again similar to the corresponding expansion recorded on heating.

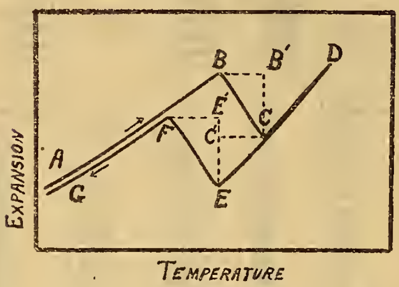

FIG. 1.—*Theoretical expansion curve for range 600 to 900° C*

The values for vacuum electrolytic iron [9] (S507, Fig. 2) may serve as reference values for the alloys. The temperature interval of contraction with heating (B, B' of Fig. 1) extended from 912 to 917° C. The corresponding interval of expansion with cooling (E', F) extended from 906 to 903° C. These intervals of temperature represent the retardations due to inherent resistances to this change, to impurities present, to our finite rate of heating or cooling. Where the retardations exceed these limits they may be assumed to be the results of alloying elements.

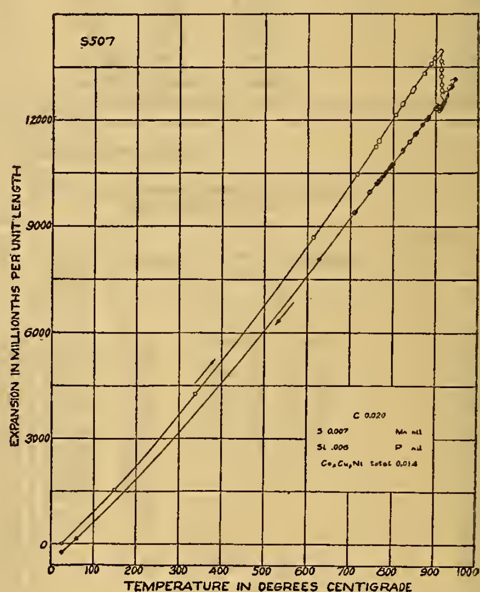

FIG. 2.—*Expansion curve for electrolytic iron*

[9] Made by Dr. A. W. Owen, of this Bureau.

The temperature interval between points C and E (CC') is not constant and varies fron 11° C for iron to an indefinite value of about 350° C on specimen S553 (Fig. 3). Specimen S484 (Fig. 4) is not included in this comparison because of the lack of proper temperature range necessary to bring out these differences.

The low expansivity of invar at room temperatures is due to the fact that this E, F region has been lowered to corresponding temperatures. Other specimens of nickel steel showing this lowering of the E, F region are: S559 (Fig. 5) and S563 (Fig. 6). These curves, including S484, give their relations to other steels at high temperatures. Excluding nickel steels, the greatest displacements are given by S546 (Fig. 7), S547 (Fig. 8), and S504 (Fig. 9). On S556 (Fig. 10) this difference is only 17° C, whereas on S546 (Fig. 7) it amounts to 110° C. Now, the usual procedure in hardening steel is to quench from some temperature a certain number of degrees above the temperature of the irregularities of the heating curve. Should it develop that the most desirable quality is present in the steel at point E (after having passed point C) rather than at point C, it is conceivable that errors approaching 100° C may have entered the quenching values.

Alloys showing the maximum differences between temperatures B and C (BB') are S504 (Fig. 9), S556 (Fig. 10), and S554 (Fig. 11). Similarly between E and F ($E'F$) we have S504 (Fig. 9), S562 (Fig. 12), and S553 (Fig. 3). Cast iron is excluded because of the indefiniteness due to growth.

Perhaps one of the most important variations is that of length change between E and F (EE'). If we assume the usual stress-strain relations as applying in this case then the stresses set up within a specimen, the outer shell of which has passed through this range before the inner, will be proportional to the length (EE'). This feature will be discussed later in connection with the results of a hardened specimen (S614). Specimens S551 (Fig. 13) and S566 (Fig. 14) illustrate this maximum expansion on cooling. The rate at which this stress is applied depends upon the value of EE', the value of $E'F$, and the rate of cooling of the different sections of the specimen.

It is interesting to note that the specimen of high silicon steel S457 (Fig. 15) gave only slight if any reversals although heated to 1002° C.

The coefficient of expansion of iron over the range 25 to 100° C is 12.0×10^{-6}. The average value for 25 of the steels tested is 11.2×10^{-6}, and the deviations (excluding high chromium and

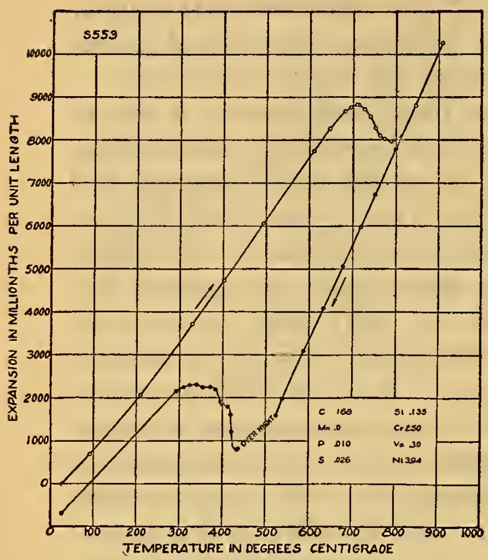

FIG. 3.—*Expansion curve for nickel steel.*

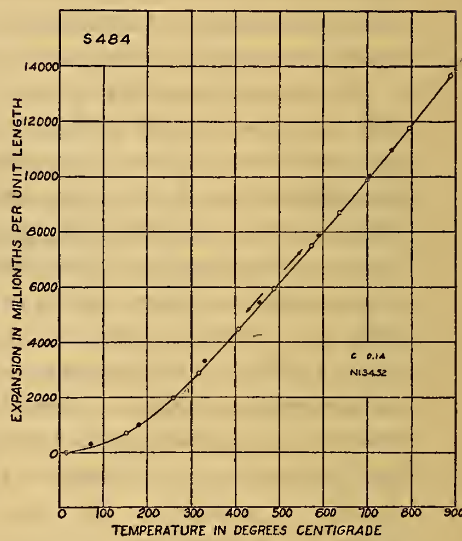

FIG. 4.—*Expansion curve for nickel steel*

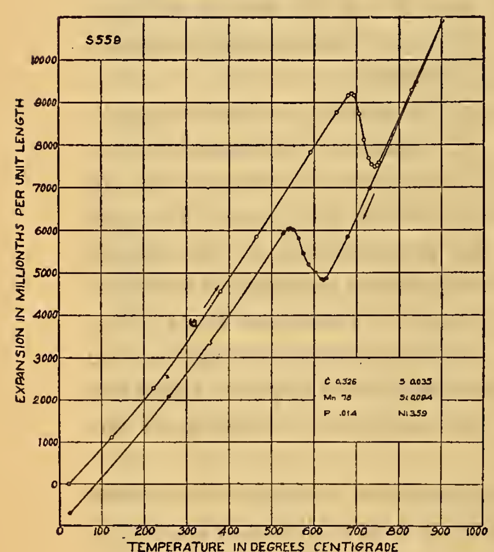

FIG 5.—*Expansion curve for nickel steel*

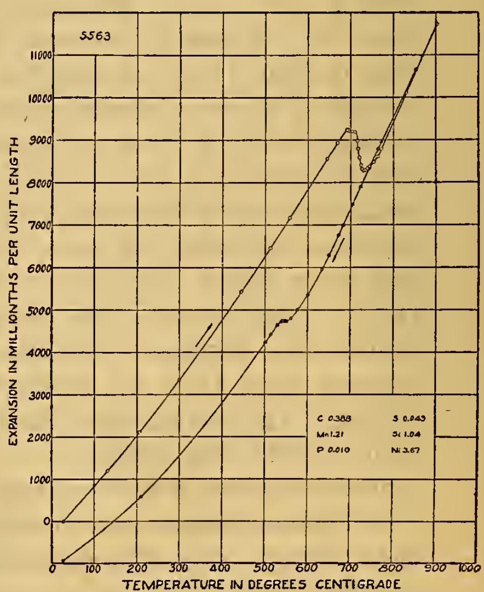

FIG. 6.—*Expansion curve for nickel-silicon steel*

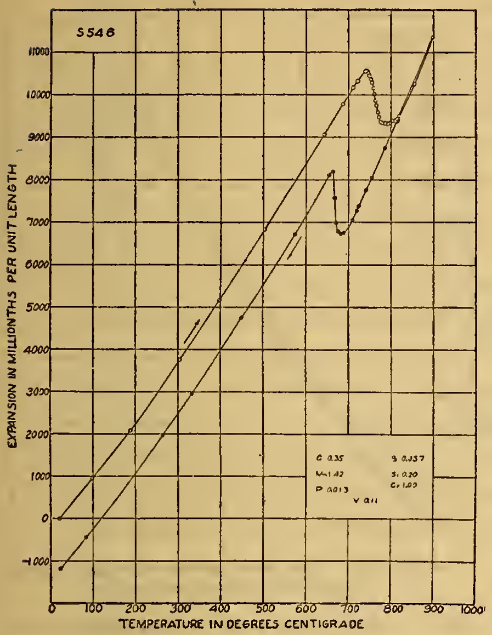

FIG. 7.—*Expansion curve for steel showing large variations between heating and cooling critical regions*

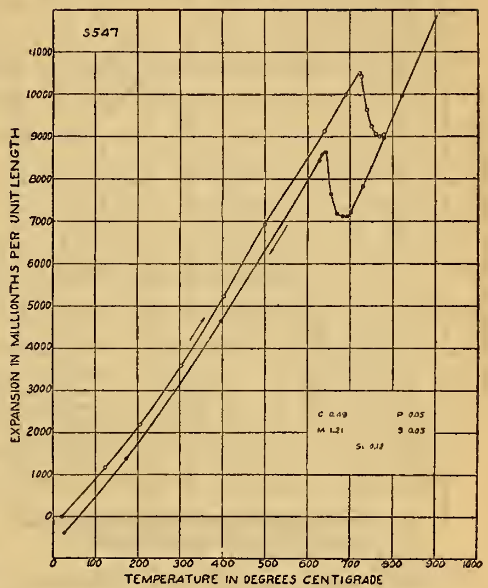

FIG. 8.—*Expansion curve for steel showing large variations between heating and cooling critical regions*

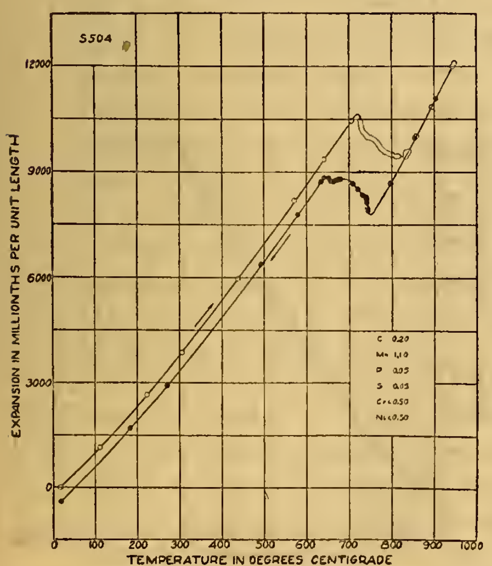

FIG. 9.—*Expansion curve for steel showing wide critical regions*

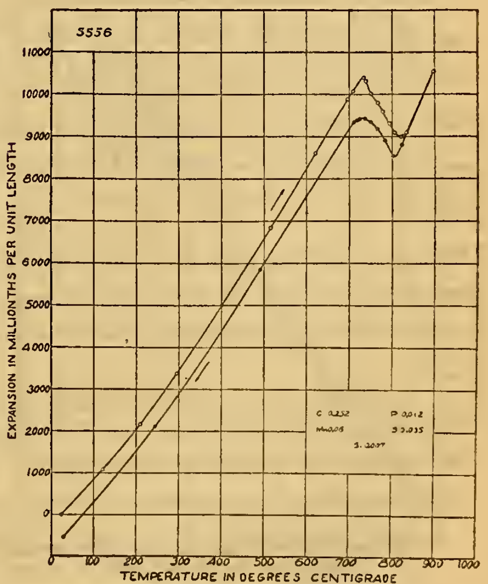

FIG. 10.—*Expansion curve for steel showing wide critical regions*

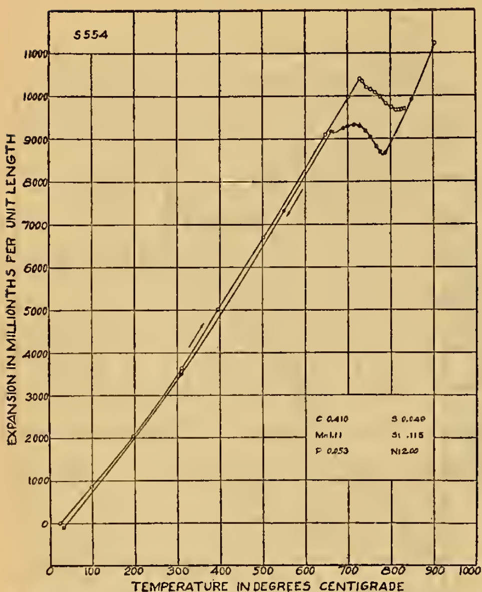

FIG. 11.—*Expansion curve for steel showing wide critical regions*

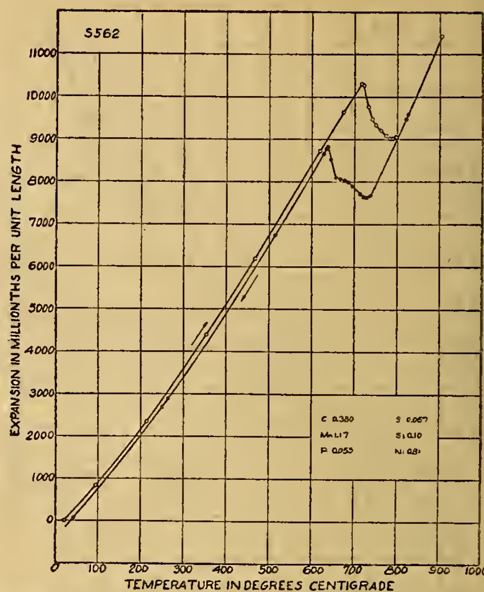

FIG. 12.—*Expansion curve for steel showing wide critical regions*

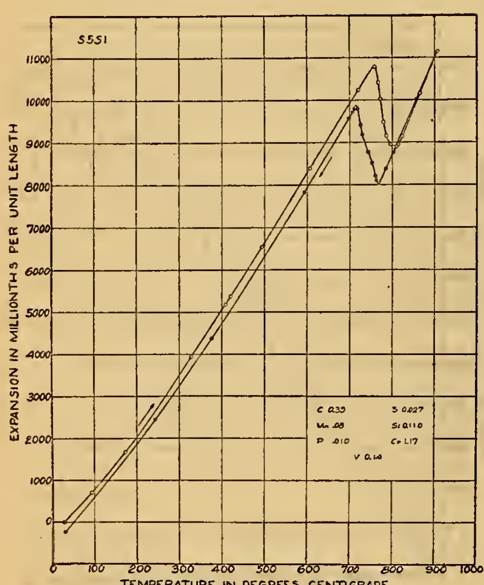

FIG. 13.—*Expansion curve for steel showing large change of dimension at critical regions*

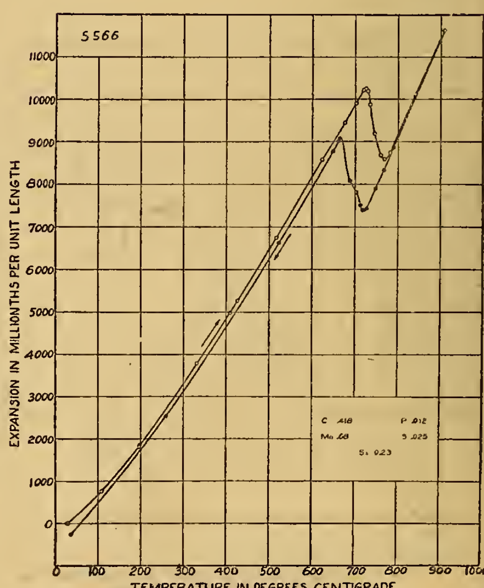

FIG. 14.—*Expansion curve for steel showing large change of dimension at critical regions*

nickel steels) are small. The average value from 25 to 600° C is 14.2×10^{-6}. Above the critical regions the values jump to values between 22.6×10^{-6} and 24.1×10^{-6}. The special high carbon, nickel, and silicon steels are not included within this range. The cooling coefficients are closely related. Within the critical region the coefficient is quite different, usually reversing sign. This reversal of sign, or expansion on cooling, may set up stresses in the hardened steel which if not properly released will cause cracking or distortion. The higher the temperature above the critical region from which the specimen is quenched and the faster the rate of cooling, the greater should be the tendency to these defects. Undoubtedly the coarser grain structure of the higher temperatures has some influence; but the cooling of the outer layer before the interior cools will set up stresses, since this outer layer adapts itself about the interior before the interior has passed through the critical region where it will tend to expand, and to stretch or crack the outer shell. The release of this stress of outer shell is shown in S614 (Fig. 16). The relative amount of this stress can be compared in the column headed "Expansion μ/m (cooling)."

The works of Honda,[10], Chevenard,[11] and others show that quenching steel may carry point *E* several hundred degrees below the normal slow-cooling position recorded in our tests. If we apply the coefficient 23×10^{-6} for the contraction rate over these several hundred degrees range for the retarded or undercooled phase of the outer surface, and apply the normal coefficient (approximately) 16×10^{-6} for the inner portions where the cooling has been sufficiently slow to permit the transformations, we justify an intensification of the above stresses.

When variations in the ratios of quenching of different parts of a surface exist, the above-mentioned inequalities in the time and rate of expansion or contraction may readily manifest their effects in warping or local cracking.

Steel No. S614, Fig. 16, is included to show the effects of hardening as related to length changes. This specimen was heated to 850° C and quenched in oil. Upon heating above 50° C we found the curve departing from the annealed-steel curve (see dotted lines for average annealed steel). The specimen was carried from 50 to 100° C and back in about 200 minutes and gave a shrinkage of about 250 microns per meter. This shrink-

[10] Honda, Tôkohu University, Scientific Reports, 8, pp. 181–205. Honda, Matsushita and Idei, J. Iron and Steel Inst., 103, pp. 251–269.

[11] P. Chevenard, C. R., 165, pp. 59–62; Rev. de Mét., 16, pp. 17–19.

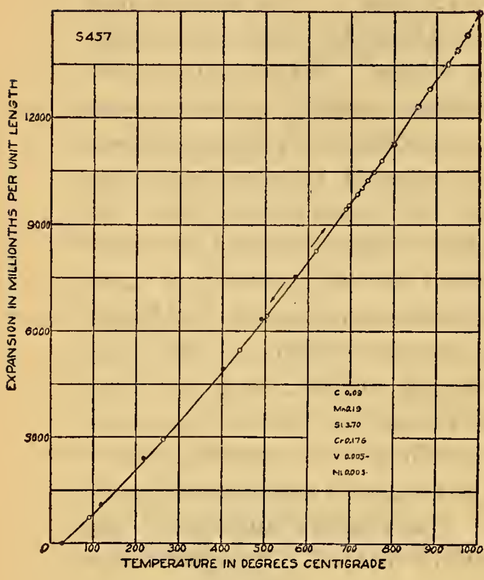

FIG. 15.—*Expansion curve for silicon steel*

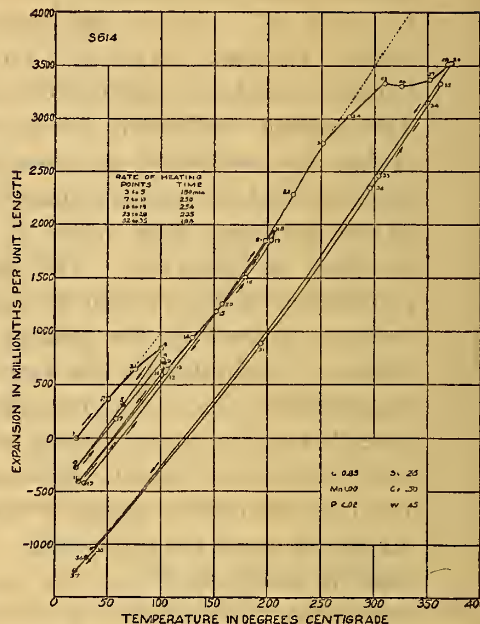

FIG. 16.—*Expansion curve for steel showing release of strains in drawing*

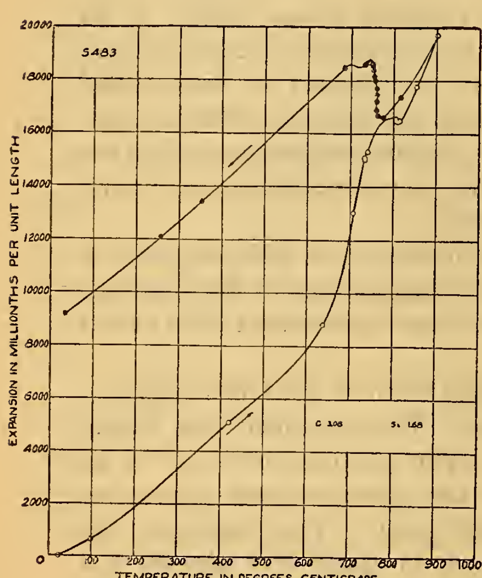

FIG. 17.—*Expansion and growth curve for cast iron*

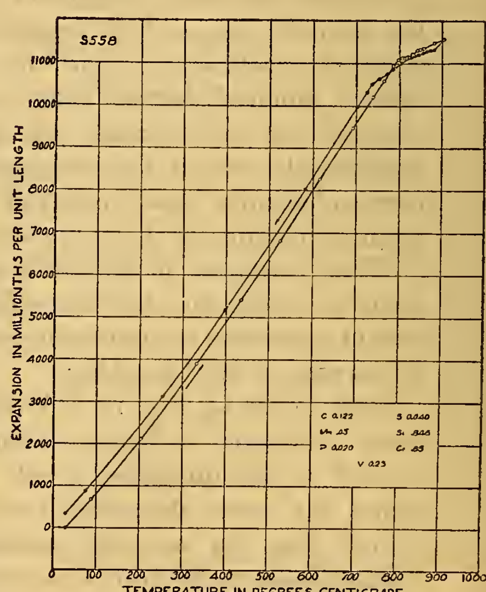

FIG. 18.—*Expansion curve for steel, showing small change of dimension at critical regions*

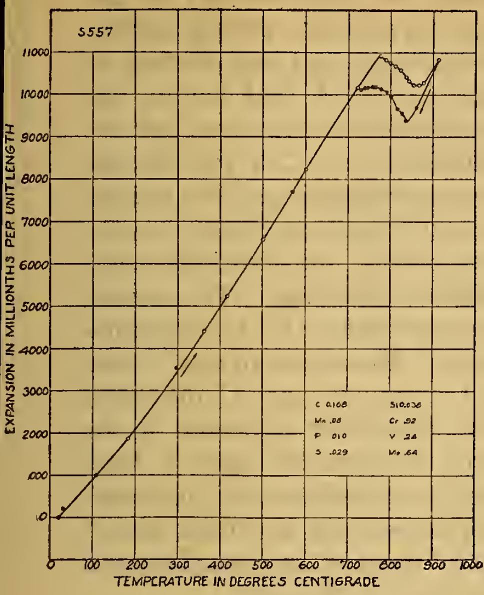

Fig. 19.—*Expansion curve for steel*

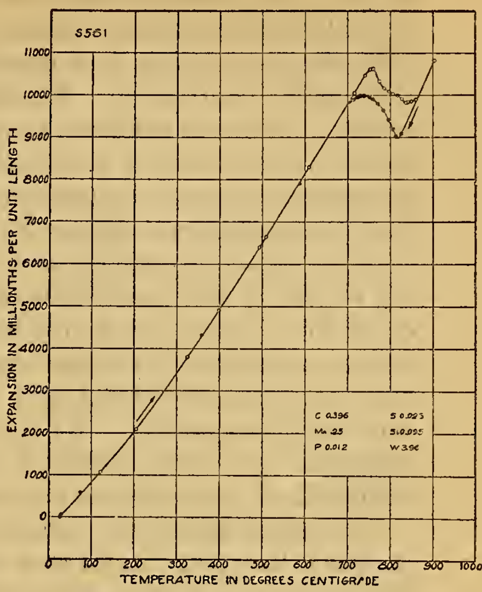

Fig. 20.—*Expansion curve for steel*

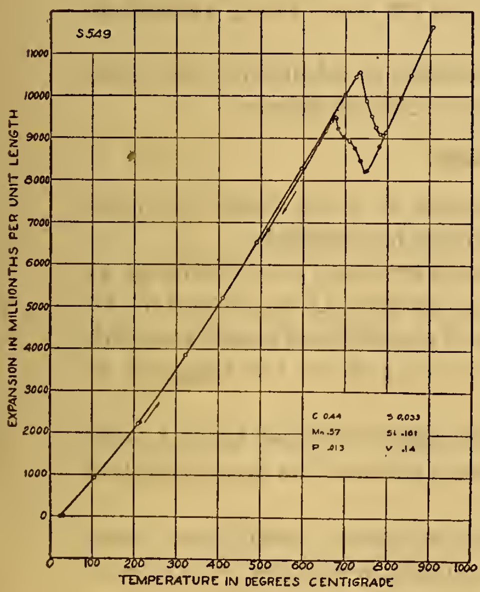

Fig. 21.—*Expansion curve for steel*

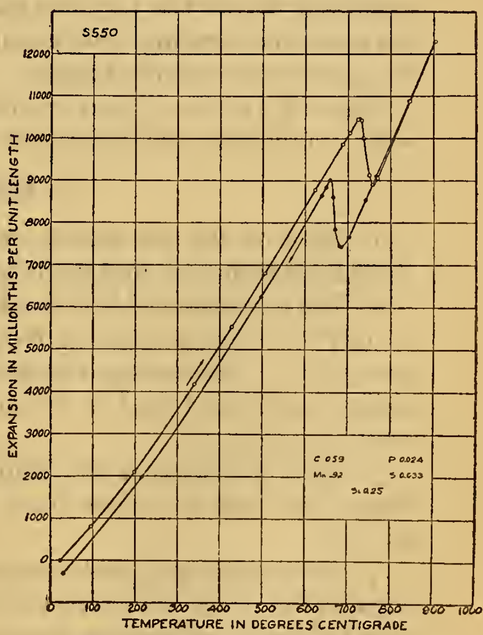

Fig. 22.—*Expansion curve for steel*

age is to be expected since the outer shell was stressed by the central portions passing through the (expanding) critical regions after the outer layers had passed this stage and had started on the regular contraction. Reheating to 100° C and holding for about 4 hours was sufficient to release additional stresses, and the specimen then showed a total shrinkage at 25° C of 400 microns per meter, or in more general terms 400 millionths per unit length. This heat treatment appears to have released practically all the stresses possible to release at or near 100° C, for additional heating to 200° C gave very little additional shrinkage. The cooling curve from 200° C crosses the heating at about 150° C; no explanation is evident for this phenomenon. Reheating to 250° C and above renewed the shrinkages, and at 310 to 350° C the effect was very pronounced. At 370° C the effect appeared to be complete and upon return to room temperature gave a total shrinkage of 1250 microns per meter, or one-eighth of 1 per cent.

This shrinkage has been shown for a specimen of chrome steel[12] on which the observations were carried beyond the critical ranges. The present curve gives greater detail of the changes.

The increase or decrease in length on cooling to 25° C was usually small and, in a large degree, indicates the lack of perfect annealing before the test was started. The maximum differences between the heating and cooling curves are closely related to the permanent length changes.

Figs. 18, 19, 20, 21, and 22 are included as additional specimens which emphasize the differences previously mentioned.

5. SUMMARY

1. Data on the anomalous expansion of a few steels and irons have been recorded, and made available for reference.

2. The expansion of iron has been determined over the range 25 to 945° C. The expansion from 25 to 100° C was found to be 12.0×10^{-6}. The average expansion of a number of steels, over this same range was found to be 11.2×10^{-6}, and for the range 25 to 600° C, 14.2×10^{-6}.

3. The coefficient for the ordinary steels which we have heated above the critical regions have been evaluated as approximately 23×10^{-6}.

4. The shrinkages and warpages of drawn steels have been interpreted in terms of the rate of expansion and rate of temperature reduction on passing through the critical regions.

WASHINGTON, November 8, 1921.

[12] B. S. Sci. Papers, No. 426, p. 513.