Mining and Metallurgical Section.

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Recent Investigations and Discoveries in Cast Iron.

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It is my purpose this evening to describe in an informal manner the results of some investigations of hitherto unobserved properties of cast iron. As cast iron is one of the oldest and most universally used metals known to the engineering profession, it would seem almost hopeless to expect to be able to find at this late day any important characteristic properties which have escaped observation and study, but I hope to prove to you that we have still a good deal to learn about the peculiar properties of this metal as distinguished from those of wrought iron, steel, or indeed any other metal or combination of metals.

It was my good fortune a few years ago to bring to light some interesting and, I believe, quite valuable properties of cast iron not then known; the new observations now to be described have grown out of those studies and have a close relation thereto, though differing radically in many respects.

In a paper entitled "The Mobility of Molecules of Cast Iron," presented to the American Institute of Mining Engineers, at its annual meeting in February, 1896, the following introductory statement was made:

"It has been generally accepted as a fact that cast iron, under the influence of repeated shocks, becomes brittle, and will finally break under a blow which otherwise it would have withstood. It will probably surprise metallurgists, therefore, to learn that experiment disproves the supposed fact, and establishes exactly the opposite. The result of about 1,000 tests of bars of cast iron of all grades, from the softest foundry mixtures to the strongest car-wheel metal, enables me to assert with confidence, that, within limits, cast iron is materially strengthened by repeated shocks or blows."

This surprising statement immediately attracted the closest attention from founders, manufacturers, engineers and scientists both in this country and in Europe. Crucial tests were made by many independent investigators under varying conditions and with all grades of cast iron. The technical papers contained numerous reports, all corroborative of the original statements, but showing much larger gains in strength than those claimed in the tables of tests appended to the paper. This did not at all surprise me because I knew from my own records obtained, but not published at that time, that my statements were exceedingly conservative. I feared that my largest gains, if published, would seem incredible, and I realized that the maximum figures given in my tables (approximating 20 per cent. increase in strength of bars subjected to mechanical shocks, as compared with untreated companion bars) would fully suffice for the purpose of establishing my claims, and I preferred that others should find still larger gains in strength on repeating the tests.

The Franklin Institute appointed a committee of experts to investigate the subject; they made and tested a large number of bars, and their report was published in the *Journal* of the Institute, July, 1898. The tables of tests in this report, covering eighty-two bars, show a maximum gain in strength of molecularly annealed bars (free from all defects), as compared with companion bars (also free from defects) untreated, amounting to 40 per cent. and a maximum gain in resilience, or bending quality, of 41 per cent.

Two important practical results have come from the publication of those investigations; one is the great increase in the practice of tumbling castings, and decrease in the practice of pickling them to remove sand burnt upon the surface, subsequent tests having shown that cast-iron bars immersed in the ordinary pickling solution (sulphuric acid and water) are weakened to the extent of about 10 per cent. as compared with companion bars not pickled, while castings cleaned in the tumbling barrel are always strengthened materially.

In Europe, tumbling barrels of very large size have been

constructed *provided with two rates of revolution* to permit of obtaining the best results. An English writer on "Foundry Practice in the Twentieth Century," Mr. Robert Buchanan, shows photographic illustrations of such apparatus in a paper (one of a series) published in the *Engineering Magazine*, May, 1903, and gives a very gratifying report of the practical value to the foundry industry of the discovery of molecular annealing of castings.

Another interesting application of this discovery has been the introduction of a clause in certain specifications for iron castings requiring that "the test bars must not be tumbled or otherwise subjected to shocks prior to being tested, but must simply have the adhering sand brushed off." The latest instance of this kind may be found in the specifications for gray iron castings recently formulated by a committee of The American Society for Testing Materials.

It thus appears that the heretofore unobserved, though characteristic, property of cast iron, of increasing in strength under the influence of shocks, has now become well known and recognized as a fundamental law governing the behavior of that metal and differentiating it in this respect from steel and all other metals under repeated shocks.

Another new observation quite as unexpected and surprising, perhaps, to metallurgists and engineers, growing out of these original studies and tending to corroborate the theory then advanced regarding the mobility of molecules of cast iron, is to be announced to you this evening.

Before proceeding to do this, however, I will ask your kind permission to indulge in a few reminiscences of a somewhat personal nature, as I think they have a close relation to what I am about to describe regarding my most recent experiments, and it is one of the compensations of advancing years to find that one's recollections of experiences of former days begin to acquire a certain interest, if not value, to a younger generation. My introduction to the study of cast iron dates back to the Centennial year, and in 1876 the total production of pig iron (as given in Mr. Swank's statistical tables) was 1,868,961 tons. In 1903 the production exceeded 18,000,000 tons, or ten times that of 1876.

Coincidentally with this enormous increase in production during these years came a large increase in the proportion of so-called "metalloids" in pig iron, viz., silicon, sulphur, phosphorus and manganese and corresponding change in the character of the metal.

I remember, for instance, the time when it was considered that anything over 1 per cent. of silicon in pig iron of No. 2 grade was rather high. Now, 1 per cent. of silicon in this grade of iron is considered rather low. It is probable that if we could ascertain the average proportion of silicon in all of the iron produced in the United States in 1903 we would find that it approximated 2 per cent. If this be correct it follows that there was produced in that year the enormous amount of 360,000 tons of silicon in the pig iron made, statistical returns of which will not be found in any of the published tables of production of metals and minerals in the United States, for it was all concealed in the iron, and was either burnt up in the converters, or in open-hearth steel furnaces, or else entered into the composition of miscellaneous castings made from this pig iron.

At the time of my initiation into the metallurgical work of an iron foundry, the quality and value of pig iron was determined by its fracture; a large open grain dark gray fracture was graded as "No. 1" iron, a closer grain metal was classed "No. 2," and so on down the scale; a variation of fifty cents, or sometimes \$1.00, a ton in the price of the different grades usually prevailed. In order to study the methods of grading iron at the fountain head, I visited, in 1881, a number of blast furnaces in Pennsylvania and other States, spending a few days or a week, as the case might require, at each. At one of the first of the large plants I inspected (long since defunct, but at that time a leading producer, with several stacks in operation), I obtained my first insight into these mysteries. Although it was summer weather, the casting-house was kept tightly closed and was consequently insufferably hot. Boards were placed over the hot sand to enable the negro laborers to walk over it, and as soon as the pigs of one cast were removed, new pig beds were made up, even before the sand

became cool enough for me to touch. On inquiring of the "boss" of the casting house why they did not open the doors to allow the steam to escape and the sand to cool quickly, he replied, "Why, you don't know nothing about making iron—it would cost us fifty cents a ton to do that, for all our iron would grade No. 2 instead of No. 1."

Here was a revelation, indeed, and from that day to this I have refused to regard the fracture of pig iron as a safe guide to its composition and value.

In a review of progress in the metallurgical arts for the year 1881, printed in a magazine called *The Penn Monthly*, February, 1882, I ventured to make the following prediction:

The improvements in the manufacture of iron and steel have been not less marked. The introduction of hotter blast has enormously increased the capacity of furnaces in the production of pig iron, and has lessened the cost. The chemistry of iron is being studied more carefully. Manufacturers are beginning to realize that pig iron is not a simple element, but is, in reality, composed of a number of substances; that its physical characteristics, such as strength, elasticity, etc., depend upon the percentages of these constituents, and that pure iron, like pure gold, is always the same thing, physically and chemically, no matter from what source it may be obtained. I believe that the time is coming when pig iron will be sold on its chemical analysis, instead of on the crude methods of grading, at present in vogue. And further, that, as the naturalist can tell the genus of an animal from an examination of a single bone, so the chemist will tell the characteristics of a mass of iron from the analysis of its component parts.

The supplanting of empirical by scientific metallurgical methods in foundries has progressed rapidly during the past ten years or so, and the recent substitution of "machine cast pigs" (cast in iron molds) in place of pigs cast in sand, has given the death-knell to the crude and obsolete methods of grading pig iron by fracture, in vogue in my youth.

Formerly the founder depended upon buying "strong" pig iron to obtain strong castings, and certain brands were celebrated on this account, bringing fancy prices, being thought quite indispensable for some castings. Most, if not all, of the famous old furnaces have gone out of existence and the progressive founder now depends upon his metallurgist to produce castings suitable for all his purposes from pig iron of heterogeneous composition. The metallurgist pays but little regard to the fracture or even to the strength

of the pig iron in the yard. He knows that the quality of the metal at the spout of the cupola depends upon a proper relation between the different component elements and that one or two of these practically control the character of the iron.

It is a common practice to-day in modern "up-to-date" foundries to draw, from one cupola in one heat, soft metal suitable for the smallest pulleys or other light castings, having tensile strength of 19,000 to 22,000 pounds per square inch, in test bars of 1-inch square section, 15 inches long, and iron of very different character, suitable for large castings, weighing perhaps 30 tons or over, having tensile strength of more than 30,000 pounds per square inch.

Recently an unusual metallurgical problem was presented to me demanding special treatment. Some small hollow castings were required for experimental purposes, about 18 inches long and $\frac{1}{2}$ inch thick, to withstand bursting strains under high-steam pressure. The peculiar requirements were that the metal must be fine grained, perfectly gray, absolutely soft, free from hard spots or "chill" and, to a certain extent, malleable. Four test bars 15 inches long and of the same thickness as the castings, molded on either side of each casting and attached thereto, were required to show tensile strength, when turned to a diameter of about .35 inch between threaded ends for the grips of the testing-machine, of not less than 30,000 pounds per square inch. This proposal was, I believe, submitted to and declined by several manufacturers who considered the conditions impracticable. The castings were made in the foundry of William Sellers & Co., Inc., and the following is a copy of a record furnished to me by the operator of the 100,000-pound hydraulic testing-machine of six test bars attached to six castings, all made on different days:

No.	Diameter.	Pounds per Square Inch.
1	.310 inches.	41,842
2	.310 "	40,533
3	.375 "	42,363
4	.342 "	43,260
5	.312 "	44,210
6	.342 "	44,565
Average	.332 "	42,795

It should perhaps be stated that there was no maximum limit of strength named, providing that all of the other conditions were maintained, and the test bars were not subjected to any treatment after being removed from the molds. The broken test bars are now submitted for your examination.

The reason for making the test bars of the same thickness as the castings and for molding them in as close proximity thereto as possible, causing them, in fact, to form a part of the casting, was, of course, to have all the conditions, such as rate of cooling, etc., alike in both, since the strength of test bars depends largely upon the rate of cooling of the metal. In order to determine this fact accurately I have made many experiments. In one case (which I have described elsewhere) I cast a solid cube of iron 15 x 15 x 15 inches, which was cut up into eight slabs 1 inch thick and these again into eight test bars of 1 inch square section. The bars were all numbered serially, making sixty-four bars in all; these were broken transversely in the testing-machine; the average strength of the bars cut from the exterior portion of the block exceeded the average strength of the interior bars by more than 50 per cent.

In another experiment four round bars were cast on end from one ladle of iron—all were 15 inches long; two were $1\frac{3}{8}$ inches diameter in the rough, and two were $1\frac{1}{4}$ inches diameter; the larger bars, which cooled somewhat more slowly than the smaller bars, when turned and pulled showed tensile strength (average) of 29,100 pounds per square inch. The smaller bars gave tensile strength (average) of 33,180 pounds per square inch—a difference of 4,080 pounds per square inch. Other similar tests gave similar results.

We do not find variations at all comparable with this in cast steel bars of the same dimensions, and the reason is not hard to find. In gray cast iron the molecules or crystals of iron are comparatively loosely tied together, the intermolecular spaces being filled with "free carbon," which may be readily brushed out from a freshly fractured surface with a common whisk. In ordinary steel there is no free

carbon, and the molecules are more closely united, hence the greater specific gravity of steel. The molecules of cast iron being far more mobile than those of steel tend to arrange themselves farther apart when the mass of molten metal cools slowly than when it cools rapidly, hence the more open grain, and tests show that the specific gravity of a mass of gray cast iron which has been rapidly cooled is always higher than the specific gravity of a mass of the same metal cooled more slowly. The denser the iron the higher is the tensile strength.

My purpose in stating these facts, some if not all of which are, no doubt, well known, is to lead you by logical steps up to the consideration and comprehension of some recent observations respecting the mobility of molecules of cast iron, which, I venture to think, will prove both novel and surprising.

I now present for your close inspection two companion test bars which were cast from one ladle of iron in one mold, from patterns of the same dimensions, viz., 15 inches long and 1 inch square section. In order to avoid possible variations due to "rapping" of the patterns, the ends of the molds were formed by iron yokes, accurately machined to 15 inches between the ends of the yokes, inserted in the mold. (See cut No. 6.) When the bars were cleaned and measured they were found to be $14\frac{1}{8}$ inches long and 1 inch square section. One bar remains exactly as cast, *the other has been caused to grow gradually in cubical dimensions* until now it is $16\frac{1}{2}$ inches long and $1\frac{1}{8}$ inches cross-section! A portion of one side of this bar has been machined in order that you may examine the finished surface, and you will observe that, notwithstanding the surprising increase in bulk—exceeding 40 per cent. over the original dimensions—it has lost none of its metallic qualities and presents a beautiful lustre and fine-grained, smooth surface.* This bar weighs precisely the same as it did before it had been caused to grow

* Dimensions of bar before treatment, $14\frac{1}{8} \times 1 \times 1$ inches; contains 14.8125 cubic inches. Dimensions of bar after expansion, $16\frac{1}{2} \times 1\frac{1}{8} \times 1\frac{1}{8}$ inches; contains 20.8828 cubic inches. Expansion in volume, 40.98 per cent.

no less than $1\frac{1}{8}$ inches in length and $\frac{1}{8}$ inch in cross-section, but the specific gravity is, of course, less than before.

A section, $\frac{1}{4}$ inch thick, of a similar test-bar before expansion, was found to have a specific gravity of 7.13. A cubic foot of this metal weighs, therefore, $444\frac{3}{4}$ pounds. A similar section of the same bar, after having been expanded about 30 per cent. in cubical dimensions, was found to have a specific gravity of 6.01; a cubic foot of the expanded metal, therefore, weighs $375\frac{1}{2}$ pounds, a difference of $69\frac{1}{4}$ pounds per cubic foot. You will naturally ask, having now examined the two bars: "How was this extraordinary increase in bulk produced while the metal remained in the solid state, retaining its original form, and showing no appearance of any alteration except in size?"

It has been accomplished by alternately heating and cooling the bar many times, and the great increase in size is a very striking corroboration, I think, of the theory advanced in the paper presented to the American Institute of Mining Engineers in 1896 of the mobility of the molecules of cast iron.

In my first experiments in making castings grow in cubical dimensions (which were made prior to the publication of that paper), some test bars were accurately measured and then imbedded in an open sand mold, forming, in fact, the bottom of the mold. The mold was then filled with molten cast iron of about the same composition as the bars and allowed to remain undisturbed until cold. The bars were then removed, placed within the iron yoke and measured by inserting a hardened steel wedge, graduated to read readily to thousandths of an inch between the end of the bar and the yoke. All of the bars had increased in length, and after six repetitions, reversing the position of the bars each time in order to keep them straight, they would no longer fit into the space between the ends of the yoke, showing that they had expanded to the full length of the mold in which the molten metal was poured. In other words, the original shrinkage of the metal had been eliminated. This process was repeated many times, the bars continuing to grow both longer and thicker with each heating.

Tests were made to ascertain the effect upon the strength of the metal, and in all cases there was a marked decrease in strength amounting, in some instances, to 30 per cent.

In the recent experiments, where a much larger growth in cubical dimensions, as in the bars now before you, has been obtained, a different method of heating has been adopted, whereby a record has been secured of the temperatures, and it has been found that there is a certain "critical temperature" which produces the greatest degree of expansion per heat.

All of the bars now shown have been heated in a case-hardening furnace provided with a pyrometer. In order to prevent scaling, or oxidation of the surface, the bars were enclosed in an iron pipe, the ends being stopped with clay. The temperature was at first maintained at about 1200° F. for one hour, the gas was then turned off and the pipe was allowed to cool slowly over night, the bars being removed and measured, when cold, on the following morning. It was found necessary to heat the bars nearly one hundred times in order to obtain an increase in length equivalent to about 1 inch per foot. Then the temperature was increased to 1450° F., when a much greater gain in dimensions occurred, averaging about $\frac{1}{16}$ inch per heat. The bar which has increased $1\frac{1}{16}$ inches in length and $\frac{1}{8}$ inch in cross-section, has been heated twenty-seven times at this critical temperature. It has, however, not yet ceased growing, and I am therefore unable to say what the ultimate expansion will amount to, but the tests will be continued until no further increase can be noted. So far, there is no evidence of disintegration of the metal, and but slight change in structure is visible to the naked eye; the bars are smooth, straight and have sharp corners.

Specimens of the expanded bars having been polished, etched and examined under the microscope, a change in structure then became plainly visible. Mr. Job, the chemist of the Reading railroad, has made some photo-micrographs of these expanded bars, and has kindly sent me a lantern slide containing two views; one of a piece of an untreated bar, the other a piece of the same bar after thirty-five heat-

ings. (See cut No. 1.) He states in his letter that the dark lines radiating in all directions, which appear in the expanded metal, are spaces (cracks) between the crystals of iron, showing that they have been "pushed out in all directions when heated, and have not returned to their original positions when cold," thus proving, I think, that the increase in cubical dimensions of the bar is due to the movement of the molecules, and not to chemical changes or changes of crystalline structure. A careful examination of both photomicrographs shows very similar arrangement of the crystals, the only material difference being that of contiguity of the iron particles.

We will now have thrown upon the screen a photograph (see cut No. 2) showing seven test bars of cast iron, all originally of the same length; two remain for comparison just as they were cast, while five have been expanded in different amounts, from 1 inch up to $1\frac{11}{16}$ inches in length, and from $\frac{3}{32}$ to $\frac{1}{8}$ inch in cross-section.*

The same picture shows a bar of steel cut to 12 inches before treatment, heated and cooled in the same manner sixty-one times; this bar has shortened $\frac{1}{8}$ inch, instead of increasing in length, as may be seen by comparison with the foot rule resting on the bar.

Other bars of steel of different grades, and also of wrought iron, all contracted about $\frac{1}{8}$ inch to the foot under this heat treatment.

The same photograph also shows a section of a bar before treatment, and another of the same bar after having been expanded by repeated heatings and coolings (*Figs. 9 and 10*).

The question naturally arises, have these observations any practical value? It would seem, perhaps, at the first glance that the decrease in strength of cast iron due to the heat treatment would limit the field of usefulness of the expansion process, and even that it may remain a mere scientific

* Since the address was given the experiments have been continued, the bars are all considerably larger than when they were exhibited, and they are still growing in size. [A. E. O.]

curiosity. A little reflection will, however, show that a loss in strength, up to, or even more than, 30 per cent., is entirely negligible in many cases, and already some interesting practical applications have been made of this discovery.

As a proof of this, I now offer for your examination a cast iron pattern of a "pin cam lever" made for a new machine. Some expensive tool-work has been put upon it, as well as upon a duplicate, the pattern having been made in two parts. When this "split pattern" was nearly finished it was found that an error had been made, and both halves were $\frac{1}{4}$ inch too short and $\frac{3}{8}$ inch too narrow. The operator of the case-hardening furnace has skilfully expanded both castings, without serious warping, to the required dimensions.

The picture now about to be thrown upon the screen (see cut No. 2, *Fig. 11*) shows a piston of a small pump which had become worn so that it was too small in diameter for further use; this scrapped casting was rescued happily for experiment, and I was informed before commencing to enlarge the piston that the polished end (having five grooves) was $\frac{6}{1000}$ inch under size. I enclosed the piston in a piece of iron pipe and heated it five times, when, on re-measuring, it was found to have increased $\frac{45}{1000}$ inch in diameter, or more than seven times the amount required to bring it up to the original size. The picture shows the piston just as it was taken from the tube after having been expanded by heat.

The next picture (see cut No. 3) shows a number of small castings, including a turned pulley, a gear-wheel blank, several cast-iron rings and bushings, which have been expanded in the same manner together with companion pieces cut from the same rings before expansion.

The next picture (see cut No. 4) shows a pattern for a casting intended to be used as a protective grating to be laid upon the floor of a core oven over the flue.

The next view (see cut No. 5) shows this same pattern, and in front of it is placed a casting made therefrom which has been in use several months, and has been heated and cooled many times. The casting was simply laid upon the

FIG. 1.

FIG. 2.

Fig. 1. shows appearance of polished section of untreated bar, magnified 50 diameters.

Fig. 2. Polished section of same bar under the same magnification heated 35 times and expanded about 35 per cent. in cubical dimensions.

This bar was cast in a mold 15 x 1 x 1 inches and was cut to 12 inches in length before the heat treatment.

No. 2.

Cast-iron test bars (*Figs. 1, 2, 3, 4, 5, 6, 7*) were all cast of same dimensions, viz.: 14 $\frac{1}{8}$ x 1 x 1 inches. Bars 1 and 3 remain unchanged; the others have grown in cubical dimensions, under the heat treatment, from 30 to 40 per cent.

Fig. 7 bar was cut to 12 inches in length before treatment; it is now 13 inches long and 1 $\frac{1}{8}$ inches cross-section.

Fig. 8 is a steel bar cut 12 inches in length, and it has contracted $\frac{1}{8}$ inch under the same treatment as bar No. 7.

Fig. 9 is a section of bar before treatment.

Fig. 10 is a section of the same bar after expansion by the treatment.

Fig. 11 shows a piston of small pump after having been increased $\frac{4}{1000}$ inch in diameter on polished end before being re ground to size.

The increase in length of the cast-iron bars is shown by the portion between the dotted lines and the right end of bars.

No. 3.

Fig. 1. Cast-iron pulley (turned) $14\frac{3}{4}$ inches outside diameter. Given 4 heatings and expanded $\frac{3}{16}$ inch in diameter.

Fig. 2. Blank gear wheel (turned) $9\frac{3}{16}$ inches in diameter. Given 5 heatings and expanded $\frac{1}{16}$ inch in diameter.

Figs. 3 and 4. Pieces of small bushing $2\frac{5}{32}$ inches in diameter. *Fig. 3* was given 20 heatings and expanded $\frac{5}{64}$ inch in diameter.

Figs. 5 and 6. Pieces of bushing $3\frac{9}{16}$ inches in diameter. *Fig. 5* was given 15 heatings and expanded $\frac{3}{32}$ inch in diameter.

Figs. 7 and 8. Pieces of bushing 5 inches in diameter. *Fig. 8* was given 16 heatings and expanded $\frac{1}{8}$ inch in diameter.

Figs. 9 and 10. Pieces of large bushing $7\frac{1}{16}$ inch in diameter. *Fig. 9* was given 20 heatings and expanded $\frac{1}{4}$ inch in diameter.

No. 4. Wooden pattern for a protective grating.

floor of the core oven over the flue and not fastened in any way. The bars in the center of the casting were heated by direct radiation from an anthracite fire about 10 feet below the casting, and were, therefore, far removed from the flames. The outside frame-work and the ends of the bars resting on the floor were protected from direct radiation of heat, and consequently remained comparatively cool.

The heated portion of the bars increased in cubical dimensions, just as the test bars have done under similar circumstances, and as the bars could not grow in the direction of their length, being held in place by the non-expanding frame, they were compelled to take the curved forms shown in the picture.

It will be observed that the outside frame of the casting matches the frame-work of the pattern, but some of the bars, having the curved form, have grown longer, the left hand bar for example, from about 22 inches, as originally cast, to $24\frac{1}{2}$ inches in length, and all have also increased greatly in thickness in the parts exposed to the greatest heat. As the foregoing tests have shown that steel bars do not expand under such conditions, it is proposed to have steel castings made from this pattern to replace the distorted iron castings, and it is expected that they will retain their original shape and size indefinitely. As these gratings do not come into contact with the fuel or flames, there will be little tendency to burning or scaling off of the metal. I do not know whether cast-steel grate bars have ever been substituted for cast iron, or whether the scaling would cause their too rapid destruction.

Although my remarks have extended far beyond the time usually allotted for the meetings of the Metallurgical Section, the subject is by no means exhausted, and the facts are presented to you in this tentative form with the hope and expectation that the new observations here given publicity for the first time in their present advanced stage of development will suffice to call forth discussion from experts, and lead, perhaps, to suggestions for new lines of investigation, as well as to other practical applications of the principles.

TABLE NO. I. RESULTS OF EXPERIMENTAL HEATINGS OF CAST-IRON TEST BAR MARKED "A," NO. 1, NOVEMBER 24, 1903.

	Number of Heats.	Length.	Expansion since last Measurement.	Total Expansion.	Rate of Expansion per Heat.
		Inches.	Inches.	Inches.	Inches.
Before Heating		14 $\frac{3}{8}$			
First Measurement	10	15 $\frac{1}{16}$	$\frac{9}{32}$	$\frac{9}{32}$	0'0284
Second Measurement	5	15 $\frac{5}{32}$	$\frac{9}{32}$	$\frac{9}{8}$	0'0187
Third Measurement	2	15 $\frac{9}{32}$	$\frac{1}{8}$	$\frac{1}{2}$	0'062
Fourth Measurement	11	15 $\frac{1}{2}$	$\frac{7}{32}$	$\frac{23}{32}$	0'0199
Fifth Measurement	8	15 $\frac{1}{16}$	$\frac{1}{16}$	$\frac{29}{32}$	0'023
Sixth Measurement	4	15 $\frac{7}{8}$	$\frac{3}{32}$	1 $\frac{3}{32}$	0'046
Seventh Measurement	5	15 $\frac{3}{4}$	$\frac{3}{32}$	1 $\frac{3}{16}$	0'0187
Eighth Measurement	1	16 $\frac{1}{16}$	$\frac{3}{32}$	1 $\frac{3}{32}$	0'0937
Ninth Measurement	4	16 $\frac{3}{32}$	$\frac{3}{32}$	1 $\frac{3}{8}$	0'0234

NOTE.—This bar is one of the regular test bars cast from first of heat of November 24, 1903. Measured 14 $\frac{3}{8}$ -in. long when cast and yielded a total expansion for 50 heats of 1 $\frac{3}{8}$ in. per 15 inches, or at the rate of 0'0275 inches per heat.

TABLE II. RESULTS OF EXPERIMENTAL HEATINGS OF CAST-IRON TEST BAR MARKED "C," NO. 2, NOVEMBER 24, 1903.

	Number of Heats.	Length.	Expansion since last Measurement.	Total Expansion.	Rate of Expansion per Heat.
		Inches.	Inches.	Inches.	Inches.
First Measurement	10	12 $\frac{3}{16}$	$\frac{3}{16}$	$\frac{3}{16}$	0'019
Second Measurement	5	12 $\frac{1}{4}$	$\frac{1}{16}$	$\frac{1}{4}$	0'0125
Third Measurement	2	12 $\frac{3}{8}$	$\frac{1}{8}$	$\frac{3}{8}$	0'062
Fourth Measurement	11	12 $\frac{9}{16}$	$\frac{3}{16}$	$\frac{9}{16}$	0'017
Fifth Measurement	8	12 $\frac{1}{16}$	$\frac{1}{8}$	$\frac{1}{4}$	0'0156
Sixth Measurement	4	12 $\frac{7}{8}$	$\frac{1}{16}$	$\frac{7}{8}$	0.0156
Seventh Measurement	1	12 $\frac{15}{16}$	$\frac{1}{16}$	$\frac{15}{16}$	0'062
Eighth Measurement	8	13	$\frac{1}{16}$	1	0'0077

NOTE.—This bar is a regular test bar with chilled ends cut off, and measured exactly 12 inches long before treatment. Middle of heat of November 24, 1903. Total expansion for forty-nine heats is 1 inch per foot, or at the rate of 0'0204 inches per heat.

TABLE III. RESULTS OF EXPERIMENTAL HEATINGS OF CAST-IRON TEST BAR MARKED "E," NO. 3. NOVEMBER 24, 1903.

	Number of Heats.	Length.	Expansion since last Measurement.	Total Expansion.	Rate of Expansion per Heat.
		Inches.	Inches.	Inches.	Inches.
Before Heating		14 $\frac{1}{16}$			
First Measurement	10	14 $\frac{5}{16}$	$\frac{1}{4}$	$\frac{1}{4}$	0'0171
Second Measurement	5	15 $\frac{1}{16}$	$\frac{5}{64}$	$\frac{1}{4}$	0'0156
Third Measurement	2	15 $\frac{3}{16}$	$\frac{1}{32}$	$\frac{3}{16}$	0'0156
Fourth Measurement	11	15 $\frac{1}{2}$	$\frac{1}{4}$	$\frac{1}{2}$	0'0227
Fifth Measurement	8	15 $\frac{1}{8}$	$\frac{1}{32}$	$\frac{1}{16}$	0'0031
Sixth Measurement	4	15 $\frac{1}{8}$	$\frac{5}{32}$	$\frac{3}{16}$	0'039
Seventh Measurement	5	15 $\frac{5}{8}$	$\frac{3}{8}$	$\frac{1}{2}$	0'0187
Eighth Measurement	1	15 $\frac{1}{2}$	$\frac{1}{8}$	$\frac{1}{8}$	0'125
Ninth Measurement	4	15 $\frac{1}{16}$	$\frac{1}{16}$	1	0'0155

NOTE.—This bar is one of the regular test bars from the last of the heat of November 24, 1903, and measured 14 $\frac{1}{16}$ inches when cast. It yielded a total expansion for fifty heats of 1 inch per 15 inches, or at the rate of '02 per heat.

TABLE IV. RESULTS OF EXPERIMENTAL HEATINGS OF STEEL BARS, SOFT STEEL, TOOL STEEL, CAST STEEL AND WROUGHT IRON.

Material.	Original Length.	Number of Heats.	Contraction.	Number of Ad- ditional Heats	Contraction.	Total Heats	Total Contraction	
							per foot.	per heat.
	in.	In.	In.	In.	In.	In.	In.	In.
Soft Steel Bar Marked No. 2	12	40	$\frac{1}{16}$	23	$\frac{1}{16}$	63	0'125	0'002
Tool Steel Bar Marked No. 3	12	28	—	—	—	28	0'023	0'0008
Wrought Iron Bar No. 4	12	28	—	—	—	28	0'035	0'0012
Piece of Cast Steel Test Bar Tested for Tensile Strength	9	10	—	—	—	10	$\frac{1}{32}$ in. per in.	0'0031

In conclusion, I desire to think you for your close attention, as well as to express my appreciation of the marked interest, indeed, I may say, enthusiasm, that you have shown both in the subject and the illustrations.

DISCUSSION.

DR. C. B. DUDLEY :—I have listened with much interest to the valuable paper of Mr. Outerbridge, and cannot help feeling, in view of the demonstration which he has made, that it is almost ungracious to say that it has been known for several years to car-wheel manufacturers and inspectors that the re-annealing of a car wheel, which means to subject it to the temperature of the annealing pits a second time, gives an increase in tape sizes, sometimes as high as three numbers. The tape size numbers differ from each other by $\frac{1}{8}$ inch. Also, it has likewise been known for quite a while that steel tires which perchance were rolled a bit too large in the tire mill, can be brought back to standard size, so as to be acceptable by putting them in the furnace over night, and allowing them to cool down with the furnace. The cause of these changes I do not think any of us understand as yet. In our studies we had associated the change with the breaking up of the combined carbon, due to heat, which is characteristic of the annealing pits. When car wheels are first cast they show about 1.25 per cent. of combined carbon. After they have been through the annealing pit, this combined carbon is reduced in amount to varying figures, from 0.90 per cent. down to as low in some cases as 0.02 per cent., the average probably being about 0.70 per cent. No careful studies have been made to demonstrate whether this change in combined carbon is always associated with the increase in size of the wheel, and I only make the suggestion as possibly explaining the phenomenon. I do not think any one has so completely studied the subject as Mr. Outerbridge, and I sincerely hope he will continue his studies until he not only arrives at the limit of the growth possible in a test piece, but also until he finds out exactly what the change is and why it takes place. As a matter of suggestion, it may be worth while to put on

record the thought that possibly in some way the change is connected with absorption of oxygen, as there seems to be considerable evidence pointing in the direction that cast iron which has been through the cupola, contains oxygen in some form.

MR. OUTERBRIDGE:—Replying to Dr. Dudley, I would say that, so far from considering his remarks at all ungracious, I think they are not only quite *à propos*, but also corroborative, as far as they go, of my investigations.

I do not claim to have created the peculiar property of cast iron of increasing in bulk under the influence of heat, a property inherent in the metal and existing from all time. I have, however, studied the phenomenon carefully, and have shown that this expansion is enormously greater than has hitherto been suspected. The increase of $\frac{3}{8}$ of an inch in circumference of a 36-inch car wheel, caused by re-annealing, or $\frac{1}{8}$ inch in 3 feet diameter—far less than the original shrinkage of the iron—is, in fact, infinitesimal, compared with the enormous increase in size of bars I have exhibited. Several have increased $\frac{1}{8}$ inch in 1-inch cross-section, as compared with $\frac{1}{8}$ inch in 3 feet in the re-annealed car wheel, and one of which has increased in volume, or cubical dimensions, over 40 per cent. Recently I heard of some cast-iron annealing boxes 15 feet long, which increased 6 inches in length after 80 heatings. This is equal to 1 inch in $2\frac{1}{2}$ feet.

Moreover, a car wheel is under very great compression strains, due to the chilling of the rim, and would naturally tend to enlarge somewhat when re-annealed, owing to the more complete relieving of these compression strains. With regard to the possible influence of combined carbon changed to graphite, I have shown that soft iron bars containing $2\frac{1}{4}$ per cent. silicon and very little combined carbon, expand much more than bars low in silicon and comparatively high in combined carbon under like heat treatment.

With respect to possible "absorption of oxygen," suggested by Dr. Dudley, I may say that in a number of experiments I have filled the tubes containing bars to be heated with powdered charcoal rammed tightly into the interstices and found little or no difference in the results.

I have, however, maintained for many years that iron melted in a cupola absorbs oxygen from the air blast. In a lecture on cast iron published in the *Journal of the Franklin Institute*, March, 1888, I attributed the remarkable effect produced upon the strength of car wheel iron by adding a minute quantity of ferro-manganese (1 pound to 600 pounds) to the fact that "ferro-manganese acts simply as a deoxidizing agent, the manganese seizing any oxygen which has combined with the iron."

This subject has engaged my thought more or less ever since that time, and I have (in a published address) attributed the difference in quality between high-chilling iron for chill rolls melted in a reverberatory furnace, and the same iron melted in a cupola, largely to this cause. Also, in my discussion on cast iron, printed in the *Journal of the Franklin Institute*, November, 1900, the following sentence appears: "Finally, I may say that I am convinced that the presence of iron oxide dissolved in the molten metal is a factor which is commonly overlooked, and is to be feared, especially in strong iron mixtures. The best deoxidizer with which I am familiar is ferro-manganese, which may be added either in the ladle or in the cupola."

The first experiments in expansion of cast-iron bars were conducted during the year 1896, long before the method of re-annealing car wheels was thought of, and even at that time an expansion far greater than that mentioned by Dr. Dudley as having been observed in re-annealed car wheels was noted and recorded.

Early in 1897, the editor of *The Foundry* saw some of the expanded bars in my laboratory, and asked permission to make a note of the curious facts in his journal. As the method of heating those bars was quite different from that which I have here described in detail, and was devised with the special view of eliminating the chance of chemical change of the bars due to oxidation of iron or absorption of sulphur from fuel, it may be well to give the following excerpt from *The Foundry* of April, 1897:

It may be interesting to know that a metallurgical friend of ours, Mr. Outerbridge, of Philadelphia, has been cultivating a very peculiar plant for

nearly a year past, which has been steadily growing in the arid soil of a foundry, and has not yet reached full maturity. The plant we refer to is a cast-iron test bar.

Two bars were cast side by side in one mold from patterns 1 inch square and 15 inches long between the ends of iron yokes. The bars when cold measured the same length, differing only 0.001 inch. When placed within the yoke and carefully measured with a graduated steel wedge, the shrinkage of one bar was found to be 0.184 inch and the other 0.185 inch. (See cut No. 6.)

The shorter bar was then heated by pouring about 10 pounds molten cast iron (of the same composition) over it, the bar forming the bottom of an open mold.

On the following day the bar was again measured, and now showed a shrinkage of only 0.15 inch. The experiment was repeated, and on a second test the steel wedge showed a space of 0.128 inch between the bar and the yoke.

Six times this test was repeated, each time the bar growing longer, and, on the seventh heating, it would no longer fit between the ends of the yoke, showing that the bar had now grown to the full length of the mold in which the iron was cast. In other words, the natural shrinkage of the metal had been entirely eliminated by the gradual increase in length due to successive heatings . . . After fifteen repetitions, the bar increased in less than before at each heating, and though it had not finished growing, curiosity to ascertain the effect upon the strength of the metal prompted the experimenter to break both bars upon the testing machine . . . This curious experiment with the "growing casting," which we have described, is not only interesting as a novel investigation, but it casts new light upon the cause of molecular changes in cast iron when subjected to alternate heating and cooling, and also furnishes valuable information as to the serious effect upon strength.

All of the investigations so far made in expanding cast iron by heat, whether by pouring molten iron over cold bars (as described in *The Foundry* of April, 1897¹, heating in a closed tube with or without charcoal, heating in a fire without any protection, or by heat radiations from a fire, as in the protective grating, producing practically the same results, tend to convince me that the astonishing change in volume is a molecular and not a chemical one, thus substantiating my original theory of the molecular mobility of cast iron.

As this peculiar property is inherent in the metal, it must have been noticed, in a way, long ago; but so far as I am aware, no careful study has ever been made of the phenomenon, and no previous knowledge has, I believe, existed of the fact that a bar of iron can be increased in bulk more than

40 per cent. over the original volume, while in the solid condition and still retaining its metallic properties.

The decrease in strength appears to bear a relation to the degree of expansion of the test bars.

MR. EDWARD B. HALSEY :—To what heat did you subject the bars in their treatment?

MR. OUTERBRIDGE :—To almost all temperatures ranging from barely visible redness nearly up to the melting point of the metal. The degree of heat found by tests with a pyrometer inserted in the furnace to be most efficacious, is about 1450° F.; at this temperature we actually obtained an increase in the length of several of these soft iron bars of $\frac{1}{16}$ inch per heat! The bar which you have examined was increased in size from $14\frac{1}{8} \times 1 \times 1$ inches in twenty-seven heats at 1450° F. to $16\frac{1}{2} \times 1\frac{1}{8} \times 1\frac{1}{8}$ inches, an increase of almost $\frac{1}{16}$ inch per heat and of more than 40 per cent. in volume in the twenty-seven heatings. At 1200° F. the rate of expansion per heat is much less, and, unless the metal be heated to visible redness, the permanent expansion in each heating is so slight that I have not attempted to measure it.

MR. HALSEY :—How were the bars cooled?

MR. OUTERBRIDGE :—We have tried slow cooling and rapid cooling, even plunging the hot bars sometimes into ice water. The rate of cooling is comparatively unimportant, but I am inclined to believe that slow cooling gives the largest permanent increase per heat for any given degree of heating.

In some cases the bars were cooled in the air; in others they were allowed to remain inclosed in an iron pipe until cold. In still other cases the bars were heated by pouring molten iron over them in an open mold, allowed to cool down with the casting, and then removed when quite cold.

MR. HALSEY :—Does the cast iron decrease in strength in direct proportion as it grows?

MR. OUTERBRIDGE :—I think it does, but have not made a sufficient number of breaking tests to absolutely prove that point yet.