

# THE TENSILE STRENGTH OF COPPER-TIN ALLOYS

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## I. Introductory

In metallurgy, as in most other applied sciences, the practice has usually preceded the theory. Rule of thumb methods have been developing since man began to take an interest in metals, and it ought not to be surprising that these empirical methods should have been brought to a high state of perfection. We have only to recall that the fundamental theory of steel was first presented in 1900, in order to see how little the theory has had to do with the real development of this subject. On the other hand, it must not be forgotten that before this theory was presented, it required a great deal of experience before the mechanic could impart to a steel a given quality. It was only with the greatest difficulty that the skilled mechanic could reproduce a certain quality even in the same piece of metal, and often the product was far from being uniform. A familiar instance of this lack of uniformity, is to be found in the variable quality of razor blades. The advent of the theory has changed this very markedly.

By controlling the temperatures in accordance with the equilibrium diagram, it is possible for even an inexperienced person to produce a very satisfactory temper in any given steel, and a little experience will enable a beginner to produce even more uniform products than the old methods would permit. The reason for this, is that the methods have been systematized and referred to definite fixed standards.

Although steel is our most important alloy, it is also the most complex, and least suited to preliminary investigations. It has been five years since the provisional diagram was published, but we are by no means certain what many of the changes in physical properties really mean. It seems reasonable, therefore, that we should have begun our investigations with more easily studied bronzes. It was thought, at the time this investigation was begun, that the constitution of the bronzes had

been sufficiently established. We soon found that we would have to revise Heycock and Neville's diagram, and that work has been done, under the grant to Professor Bancroft. We have now succeeded in clearing up the constitution of the bronzes, and also in obtaining some interesting results as to the relation between the constitution and the tensile strength.

Because of the great difference of properties produced in steel by heat treatments, this metal has always been regarded as a very special material. That similar changes might be produced in other alloys has been suspected, but the method of investigation has been to subject them to the same kind of treatments that are given to steel, and if the metal did not show similar differences it was then regarded as possessing none of the changes which steel shows. It is, of course, obvious that such a method of experimentation will fail to detect important relations in metals other than steel, unless said relations occur at temperatures nearly the same as those in steel. Unfortunately for this method of investigation, most metals possess their own peculiar properties, and where they show transformations similar to steel, they are apt to occur at temperatures widely different, so that the same treatment which is given steel, will fail to produce the similar transformations in another metal, for no other reason than that the changes occur at some different temperature. An intelligent study of the nature of each series of alloys will detect these transformations where the empirical methods will miss them entirely.

For example, heating a piece of steel to a red heat and quenching it in water will harden it. A similar treatment softens bronze. This quenching strengthens both steel and bronze. It softens, but does not strengthen brass. Annealing renders steel more ductile; it renders brass more ductile; it greatly diminishes the ductility of bronze. The reason for these very different results of heat treatment is easily explained by a study of the constitution of the alloys. It seems rational, therefore, to begin the study of the constitution of alloys, before wasting time in trying to determine their physical properties. Engineers have been determining the properties of materials for

many years without being able to give to their results any general significance. It is the duty of the physical chemist to point out the general relationships which exist between the constitution and the physical properties.

It might be thought that technical men would gladly support investigations of this nature, so directly are the results applicable to technical problems. A review of the literature will show that such is not the case. Few technical men have the patience to pay for the results which do not have an immediate practical application, however necessary they may be to the theory. In France, where most of the work on the nature of special steels has been done, the investigators confine themselves to a very few selected alloys. Usually only two different concentrations of carbon are tried, and instead of determining the equilibrium diagram, they have to content themselves with the microstructure of the particular compositions examined. What the general relations are they do not attempt to determine. Such investigations can only be regarded as a make-shift.

We have been speaking altogether of the necessity of more complete work for the development of the practical side of the science, it is even more necessary for the pure science. The subject of geophysics is now absorbing the attention of a number of scientists, and such men find themselves seriously handicapped for lack of more exact information as to what happens in fused magmas. The methods which are being used in the investigation of rock magmas are precisely the same as the methods used in the study of alloys, with the difference, that the alloys are much the simpler case. Every discovery which the student of alloys makes, will be of direct assistance to the student of geophysics. For that reason also, it seems that alloy studies should be amplified as much as possible.

The investigation here reported on has been under way for the past year at Cornell University, under a Carnegie grant to Mr. Shepherd. Parallel work has been done in the department of chemistry by Messrs. Shepherd and Blough, and in the experimental engineering laboratory of Sibley College, by Messrs. Upton, Shepherd and Blough.

Except for the experiments of Thurston, there has been little previous work on the engineering strengths of the bronzes. Records of tests are scanty. In 1842, Mallet<sup>1</sup> reported upon the strengths, color and character of fracture, order of hardness, order of malleability, and order of fusibility of the bronzes. He used sixteen pieces to cover the range from copper to tin, and of these half lie in the useful end of the series. Wade,<sup>2</sup> Dean, 1868-1869, and Uchatius<sup>3</sup> all experimented with bronze for cannon, but they worked over very small ranges of composition, and were concerned chiefly with methods of increasing strengths by mechanical manipulation.

The experiments which have become classic in this line are those of the U. S. Board for Testing Materials, conducted by the Committee on Alloys, under the chairmanship of Dr. R. H. Thurston.<sup>4</sup> This work was very extensive, ultimately covering with transverse, tension, and torsion tests the whole of the ternary alloys of copper-tin-zinc. Because of its extensiveness, no part of this investigation could be gone into in great detail, and thus we find that only twenty pieces were tested for all the tensile properties of the copper-rich bronzes, a range of composition from 100 down to 65 percent of copper, which includes all bronzes of industrial importance.

The preceding investigations were all handicapped in one point; the internal chemical and physical constitution of the alloys tested was unknown. This must not be taken superficially to mean that analysis for the ultimate percentage composition was not readily made, although there was not then a method of separating copper and tin that gave a probable error much less than one-half of 1 percent. It is to be understood rather in the sense that no one knew whether the elements in the alloy were combined in chemical compounds, or solid solutions, or mere mechanical mixture, or in other ways. The rise of physical chemistry in the last ten years, the gain in knowledge

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<sup>1</sup> Phil. Mag., 21, 66 (1842).

<sup>2</sup> Report of experiments on metals for cannon, Phila., 1856.

<sup>3</sup> U. S. Ordnance Notes, No. 40, Wash., 1875.

<sup>4</sup> Report on properties of Copper-Tin Alloys, Washington, 1879.

of the changes in constitution of alloy series with heat treatment and composition, have made advisable and necessary the repetition of the tests of engineering properties not only of the bronzes, but of practically all of the metallic materials of engineering.

It is evident that the engineering properties of alloys, such as tensile strength and ductility, transverse strength, shearing strength, etc., must be closely connected with the internal chemical and physical structure. The equilibrium diagram shows, by its boundary lines of regions, where such structure changes; the regions or fields it outlines have each a definite structure characteristic. The investigation of tensile strengths with which this report is concerned is believed to be one of the first sets of tests to be made with the use of the freezing-point diagram, and shows how well that diagram can be relied upon in the prediction of the critical points in such research.

In Fig. 1 is given that portion of the copper-tin freezing-point diagram which includes the alloys containing more than 50 percent copper. The diagram is taken from the data of Heycock and Neville,<sup>1</sup> as modified by the more recent work of Shepherd and Blough.<sup>2</sup>

The coordinates are temperature and concentration, or percentage composition. The lines of the diagram mark the places where some physical or chemical change occurs in the alloy. The upper full line is the "liquidus," above which the alloys are completely molten. At the liquidus, crystals begin to separate out from the melt. The round-dotted line is the "solidus," below which the alloys are completely solid. Between the liquidus and the solidus the alloy is in a partially frozen state and consists of a "mother-liquor" more or less filled with a network of solid crystals. The region marked  $\alpha$  means that anywhere within that area the alloy, if in a normal and stable condition, exists only in the form of  $\alpha$  crystals. These crystals are composed of a solid solution of tin in copper; with

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<sup>1</sup> Phil Trans., 202 A, (1903).

<sup>2</sup> The complete diagram for the copper-tin alloys forms the subject of a subsequent paper by Messrs. Shepherd and Blough.

anything between 100 and 87 percent of copper the form of crystallization is the same. So  $\beta$  and  $\gamma$  are other solid solutions having definite crystal forms; and what was called  $\text{Cu}_3\text{Sn}$  by Heycock and Neville, is another,  $\delta$ , with a narrow range of concentration, instead of being as long supposed a chemical compound. The only chemical compound in bronzes containing more than fifty 50 percent copper is  $\text{Cu}_3\text{Sn}$ . Besides the idea of

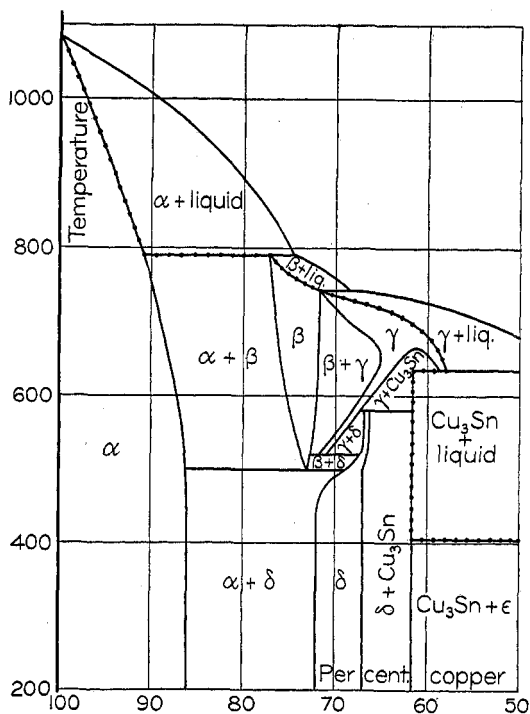


Fig. I

a definite crystalline form being characteristic of a solid solution over a considerable range of concentration and temperature, one must grasp the conception that chemical changes in the solid are of frequent occurrence. Thus below  $500^\circ$   $\beta$  is an instable form, and if cooled slowly past that temperature, it rapidly breaks down to  $\delta$  crystals. How complicated the changes in the solid may be can be seen from the fields for  $\beta$ ,  $\beta + \gamma$ ,  $\gamma$ ,  $\gamma + \delta$ ,  $\beta + \delta$  etc., Fig I.

Let us trace the freezing of a 95 percent alloy. Follow down the 95 percent line; freezing is seen to begin at  $1050^{\circ}$  C. At that point  $\alpha$  crystals begin to form and separate, the mother-liquor becomes richer in tin. As cooling progresses, more and more freezes out, and the mother-liquor composition follows down the liquidus (the upper curve) so that at  $950^{\circ}$ , for instance, the mother-liquor contains 86 percent of copper. The  $\alpha$  has meanwhile built up a crystalline network all through the freezing mass. The 95 percent line cuts the solidus at  $910^{\circ}$ , meaning that at that temperature the whole alloy becomes solid. The first  $\alpha$  crystals contained more than 98 percent of copper; but diffusion and interchange are quite rapid, so that the final cold mass will be uniform  $\alpha$  crystals of 95 percent composition. If we had started with an 85 percent alloy, freezing would have begun at  $955^{\circ}$ , and been complete at  $790^{\circ}$ . The product would in this case have been a mixture of two forms of crystals,  $\alpha$  of about composition of 92 percent, and  $\beta$  of 75 percent, the  $\beta$  coming from the final freezing of the mother-liquor. As cooling progressed there would be a breakdown "in the solid" of  $\beta$  to  $\delta$  and the final cold alloy would be a mixture of  $\alpha$  and  $\delta$  crystals.

The reaction velocities of internal change in alloys are very small or zero at ordinary temperatures, and do not become rapid until temperatures approach or exceed a red heat. This fact makes it possible to raise a specimen to a certain temperature, hold it there a sufficient time for it to obtain equilibrium, and then by sudden cooling, usually water quenching, to fix the structure normal to that temperature so that the structure is held indefinitely and can be studied or utilized at leisure. The hardening of steel is an example of such treatment, retaining and using at ordinary temperatures characteristics of the metal which are thermally normal at low red heat.

Thus the above description of what occurs in the freezing and cooling of a bronze is true only if the rate of cooling is low enough to enable the mass to maintain throughout, a condition of thermal equilibrium. Suppose one let the 85 percent alloy cool slowly to  $650^{\circ}$ , and then quenched it in water. He would then fix in the solid the  $\alpha$ - $\beta$  composition and properties the piece

had before the quenching. If one desires to know the strength, hardness, ductility, or any other properties of pure  $\beta$  crystals he takes a 75 percent bronze and quenches it from between  $600^{\circ}$  and  $700^{\circ}$ . This power of fixing properties by quenching is a fact of the highest importance. The growth of crystals with time at high temperatures, changes of composition due to diffusion, and control of the cooling rate, are the means which underlie and bring about all modifications of the strengths of materials by heat treatment.

The best way to develop the structure and properties normal at a given temperature is first to chill-cast the specimen, then to anneal, holding it at the desired temperature for such a time as is found necessary, and to fix by quenching. Chill-casting gives a very uniform piece with minimum crystal size. Because of this small crystal size, meaning a very close and intimate mixture of components, equilibrium is far more readily reached when heat treatment is made, for diffusion need occur only through very small distances. The more rapid the chilling the better. Chill-casting has been shown to be so effective in securing close mixture of components that even copper and lead, the alloys of which normally separate into two liquid layers, can be obtained in fairly uniform ingots. If there be any tendency to liquation it is checked by chill-casting.

Keeping the preceding discussion in mind, the plan used in carrying out the present investigation was as follows: (1) Chill-casting, to get a very uniform test-piece, with minimum crystal size; for it is generally thought that the smaller the crystal, the higher the strength of the material. (2) The pieces to be given prolonged heating at various temperatures; in order to fully attain the crystallization and structure normal to those temperatures; the heating followed by fixation of properties through control of cooling rate. (3) Testing.—It was decided to carry through certain series—(1) one series of alloys was tested as cast; (2) one series was heated for a week at  $540^{\circ}$  C, and water quenched, giving the properties of  $\alpha$ ,  $\beta$ ,  $\gamma$ , etc., as shown by following the  $540^{\circ}$  ordinate through the freezing-point diagram; (3) a third series was heated for one week at  $400^{\circ}$



and furnace-cooled, in order to find the properties normal to slow-cooled bronzes, of compositions  $\alpha$ ,  $\alpha + \delta$ ,  $\delta$ ,  $\delta + \text{Cu}_3\text{Sn}$ , etc.; (4) to show how the heat treatment might be used commercially, a series was carried through where the pieces were simply heated up to a low full red and then quenched, corresponding to about  $650^\circ$  heating and quenching. In addition to these regular series there were many miscellaneous heat treatments, with various times of heating and various temperatures.

## II. Making the test-pieces

For the purpose of studying the effects of changes of composition and heat treatment, it is essential that the test-pieces be perfectly uniform in composition. The best way to avoid the effects of liquation, is to chill-cast the test-piece. For the same reason it is desirable to cast the test-piece in the form in which it is to be tested. Machining the test-pieces might change their composition, and will have some mechanical effect which could not be neglected without a special investigation for each particular alloy. In chill-cast copper-rich bronzes the liquation is negligible.

The temperature of pouring, has only one effect on an alloy. The excess heat imparted to the mould determines the rate of cooling, and thereby, the grain size. In the present research, the temperature of pouring was very uniform and, owing to the nature of the alloy and to the process of chilling, would have a minimum effect.

The materials used for making the test-pieces were electrolytic copper, of 0.9998 purity, and tin, 0.999 pure. Thus the influence of even minute quantities of other metals was avoided. For convenience of operation, the original 20-pound copper pigs were recast into 0.75-pound pieces or smaller. The tin was already in narrow bar form.

The melting was done in a gas furnace which was placed at our disposal by the chemical department. This was an air blast-furnace which proved well able to reach and hold the necessary temperature, about  $1200^\circ \text{C}$  being desired in the melt of pure copper, requiring a furnace temperature somewhat higher.

The heat was such as to cause the fire-clay furnace lining to soften and flow slowly. This fluxing of the furnace lining is partly due to oxide of copper. At 1200° C copper has a very appreciable vapor tension. Three linings have been used in a year and a half. To increase the efficiency and reduce the amount of gas used, the furnace was fitted with a thick non-conducting jacket, and the valves were calibrated.

Graphite crucibles were used, and 1900 grams (4.25 pounds) of copper constituted a maximum charge. Ordinary "Hessian" crucibles would not last in the service more than two or three melts, while the graphite is good for thirty to fifty.

The original melt for casting a given composition totaled around 1800 grams, or somewhat less than 4 pounds. The weighing out was accurate to 1 gram, or 0.06 of 1 percent. After being broken in the testing machine, the castings were remelted and recast, and this was done with some metal nearly a dozen times. With zinc, as in brasses, this would be impossible without analysis for composition of each melt. No appreciable error is introduced in the bronzes. The greatest shift of composition, due to oxidation or burning out of tin, occurs in the lowest melting bronzes tested, 70 percent of copper, and there it was only 1/10 of 1 percent in 7 or 8 remeltings; that is, it was not large enough to need consideration. With higher copper to start on, the shift was much less; in a 98 percent alloy it could not be detected. After a number of recastings mentioned, the metal was analyzed, and tin added to correct the composition. The compositions used for the tests were in percents of copper 100, 98, 96, 94, 92, 90, 87, 84, 81, 78, 75, 70. These compositions were thought sufficient to cover the ground thoroughly.

(a) *Preparation of the Mould.*—Because of the rapid chilling desired it was at first thought that a copper mould would be the best to use. Copper was preferred to iron because of the gases which iron evolves when heated. A copper mould was made, but was found impracticable. The chill was so rapid that the mould would not fill, or if heated so that it would fill, the castings were defective in being full of bubbles of trapped air.

Sand casting was given a trial. The surface of the castings was then very bad, and machining difficult, while the pieces themselves were imperfect. The sand pile available was small, and burned out. Compare Thurston, report on the properties of the copper-tin alloys, page 296: "The first casting was made in dry sand moulds, but so much trouble was given by irregular surfaces and blow-holes that recourse was had to a cast iron mould, with better results." Thurston cast straight bars of uniform cross section. In this form of casting a metal mould can be used.

When the metal was poured at too low a temperature into the cold mould it was sometimes slightly chilled, giving an irregular surface. This was remedied by heating the mould to a temperature somewhat below the melting-point of the alloy, the highest temperature being given it in casting alloys containing the largest percentage of copper. In all cases the mould was placed in a vertical position while the metal was being poured and cooled.

Then trials were begun with a material which has been found ideal—artificial graphite. The graphite is easily worked, and takes a beautiful surface; the cast pieces come out so smooth and accurate that machining is unnecessary. The mould can be made to cast the shape and size desired for the finished test-piece. The moulds are relatively durable; one is good for 75 to 200 castings. They fail finally in three ways: by flaking off of the surface, due to a crack in the original plate; by breaking off of small corners or thin walls, if a piece is left too long to contract in the mould; and by a gradual softening and powdering off of the surfaces against which the hot metal comes.

The evolution of the form of mould finally adopted was gradual. The first form, I in Fig. 2, was a simple sprew running down to a test-piece, with a vent at the other end of the piece. The halves were matched with dowel pins. Difficulty was found with the mould not filling, and was obviated by enlarging the sprew and heating the mould. The greater trouble was trapped air, which made one likely to cast pipes instead of solid test-pieces. The rather sharp tapers on the test-piece made breakage in the

mould from cooling strains frequent. In II these tapers were made more gradual, and the air vent was made larger, becoming a small riser. The catching of air bubbles in the cast piece still occurred, and therefore in III, a vented air trap was put into the sprew. A projecting fin along the top of the test-piece was also tried, in the hope that the air bubbles would rise

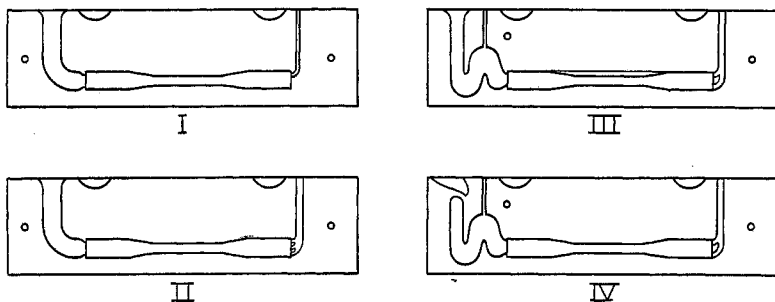


Fig. 2

into the fin, and leave the test-piece itself sound. The fin idea was worthless. Finally, it was reasoned that the air bubbles must get into the metal as it splashed in pouring into the sprew, and that the best cure was prevention. Therefore the "centrifugal sprew" (IV) was invented, shown in Fig. 3. The

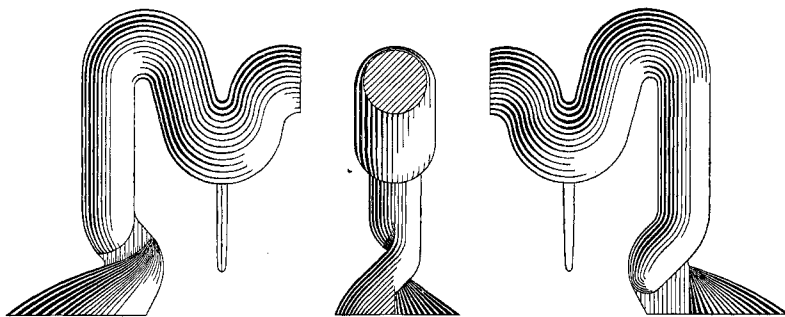


Fig. 3

diagram is self-explanatory; the metal was gently caught and sent down, flowing smoothly down the outside of the sprew cavity from the action of centrifugal force. With splashing stopped, the trouble from trapped air bubbles largely ceased. The air trap in the sprew was still retained, as a good precaution.

The halves of the mould were clamped together between two plates of  $\frac{3}{8}$ -inch iron, which were hinged at one end and fitted with a wedge lock at the other. Thus the whole combination could be lifted into or out of an improvised furnace, built of bricks and heated by blast-lamps. In operation, the mould was clamped together, put into the furnace and heated; and when the desired temperature (black or low red heat) was reached, the lid of the furnace was removed, and the pouring made. Then the mould was lifted out of the furnace, unclamped, the casting taken out and quenched in water. The test-piece, before quenching, was usually at or just below a red heat.

The mould heating furnace was shortly done away with, as the form of mould had become such that the heat kept in the graphite from previous castings was sufficient to insure filling. Not having to lift the mould, the iron clamping strips were left off. The mould was simply set up on the cement floor, and the halves held together by three or four bricks laid at each side. This method also did away entirely with breakage of pieces in the mould from cooling strains, because the contracting piece readily spread the mould by means of the long tapers. The contraction in a test-piece 22 cm. long amounts to about 2 mm.

A casting trouble that no variation of mould can rectify is the pinholing, or sponginess, which is due to gases occluded in the molten metal. Molten copper, and molten bronzes down to 85 percent copper, have the power of absorbing gases. When freezing begins these gases are set free with the result that the mass of the casting is filled with tiny bubbles of sizes from a pin-point to a pinhead. The only way to avoid this is by proper treatment of the melt in the furnace. The absorption of gases is roughly proportional to the time the metal is held molten. Hence the furnace was run hot and the time of melting kept as short as possible. The metal must be gotten hot, for if poured too cold, it is practically certain to trap air bubbles. It was found also that the occluded gas was much worse in the top of the melt, and therefore the practice was adopted of pouring off the top portion of the metal in the crucible into an ingot mould, and then pouring the test-piece casting. The little ingot froze, re-

jected its gas, and while still red hot was returned to the crucible, so that not much heat need be lost by this precaution. The waste gases of the furnace were used to reheat the metal about to be put into the crucible; by thus avoiding the direct introduction of cold metal the furnace temperature was kept high.

Molten, or even hot copper has a great affinity for oxygen. In the crucible, if air has access to the melt, the oxidation is so rapid as to make the metal simmer and bubble. Copper oxide is much weaker than copper, and renders a casting in technical language "rotten," *i. e.*, absolutely worthless. The remedy for the oxidation is exclusion of the air, which was readily done in this case by filling the top of the crucible with an atmosphere of illuminating gas, brought in through the furnace lid by a porcelain tube. Commercially some flux, such as charcoal, would be used to stop oxidation. Its inefficiency is shown by the necessity for poling.

For the original melt of any composition, the copper was always put in first. Usually a piece of soft graphite was put in with the copper, and would be floating on the top when the copper melted down. When it had become thoroughly hot, the molten copper was stirred or "poled" with a rod of graphite or carbon. Then the tin was added, and well stirred in. This stirring with a graphite rod was mainly to make sure that there should be no copper oxide in the melt.

The difficulty of casting pieces varies considerably with the composition. Occluded gases are worst above 90 percent and below that rapidly cease to make trouble. Indeed, it seems that below 85 percent the melt no longer has the power of occluding gas. Oxidation goes out the same way; though it may be severe in an 87, it is rarely found in an 84 percent, and never at all in any percent below 84. The trouble with air holes, from trapped air, has its main cause removed when the mould is properly formed. It may occur in any composition if the metal is poured too cold. It is not likely to occur below 84 percent, because the melting-points are then so low that there is little chance that the metal will be poured cold. To sum up then, there is not much difficulty at or below 84 percent in getting

any desired number of good castings. The worst compositions to cast are in the range 94 to 87 percent. There every trouble must be met and in avoiding one, another is almost sure to be increased. The result was an average in this range of less than 60 percent of good castings.

After the casting came the heat treatment. In order to give the prolonged heating at high temperatures, two annealing furnaces were built. Each furnace consisted of a fire-clay muffle about 15 inches long, so built in with tile brick that the gases from a triple or quadruple Bunsen burner passed along the bottom of the muffle, back along the sides and back again along the top. The test-pieces, 20 to 25 at a time, were put into the muffle and sealed in with clay. To prevent oxidation a stream of illuminating gas was passed constantly through the muffle, in at one end and out the other. A tube for a platinum platinum-rhodium thermocouple was sealed in, so that the thermocouple could at any time be used to get the temperature in the middle of the muffle. Temperature regulation was made by adjusting the gas supply. These furnaces were quite satisfactory; they could be kept within  $20^{\circ}\text{C}$  each side of the desired temperature, and usually within  $10^{\circ}$ .

Two temperatures were used for runs. One series of compositions of test-pieces was put in and run for one week at  $540^{\circ}\text{C}$ , and water quenched when taken out. Another series was run at  $400^{\circ}\text{C}$  one week and allowed to cool in the furnace. Theoretically, furnace-cooling the  $400^{\circ}$  series would not differ in effect from quenching.

Many shorter heat treatments were made, where pieces were heated for three hours or less. These heatings were made in a regular gas-fired assay muffle furnace. The muffle was partially filled with fine sand and the pieces pressed down into that. One regular series of heat treatment was made thus, where the pieces were simply brought up to a heat between low and full red and then water-quenched. With the compositions below 90 percent, especially 81 and 78, several different combinations of temperature and time were tried.

Very little machining of test-pieces was done, because few

were made before the development of the graphite mould made turning up unnecessary.

### III. Testing

While it might in some ways have been desirable to make the test-pieces of the same size as the standard for wrought iron and steel, the great expense of the chemically pure materials used made this impossible. Therefore the size of the graphite plates available for the moulds and the capacity of the furnace which had to be used for melting were allowed to control the test-piece size. The dimensions chosen were roughly one-half those of a standard tension piece—more definitely 9 inches long over all, with the cylindrical test portion in the center about 0.42 inch in diameter and 3 inches long. The grips at the ends were  $\frac{3}{4}$  inch in diameter. A few of the first test-pieces made, those which were turned, had smaller diameters.

When a wrought iron or steel piece is tested, the elongation is made up of two parts: first, a fairly uniform stretch throughout the whole length of the cylindrical portion; and second, for a length of  $\frac{1}{2}$  inch to 1 inch on each side of the break, there is superposed on the first a greater local elongation in what is called the "neck" of the break. Obviously, then, if the length under observation be shortened so that the neck forms a larger part of the whole, the ultimate elongation found will be much increased. Hence in testing these materials it is absolutely essential in order that tests may be comparable with each other that the same ratio of diameter to length of observed portion of the cylinder be maintained. This is the reason for the existence of standard forms in iron and steel test-pieces. It is not necessary that pieces be of the same size, if their forms are similar; that is, a piece 8 inches long and  $\frac{1}{2}$  inch in diameter will give the same results as one 4 inches long and  $\frac{1}{4}$  inch in diameter, or 16 inches long and 1 inch in diameter, barring the fact that the working of the material in manufacture affects the outer part of a rod more than it does the center.

In the bronzes the local effect of necking does not occur, or it is very small. The cylinder draws down straight and



uniformly to the break. Hence the great care about the ratio of length to diameter of test-piece is unnecessary, for with the same diameter of piece the length observed may be changed at pleasure and the percent elongation found will be practically unaffected. Therefore, these tests made upon half-size pieces, though the ratio of length to diameter is less than the standard, are yet perfectly typical and are just as good as if made upon standard size. The only disadvantage of measuring a short length of cylinder is, that to get the same accuracy in the percentage extensions greater accuracy of absolute measurement is necessary.

Just as in the iron test-piece the center is filed down to insure the locality of the break, the bronze pieces were cast with the center of the cylinder about 0.01-inch smaller in diameter than the ends. They never broke elsewhere unless there was some internal flaw.

The testing machine used was the 100,000 pound Riehle which is by far the most convenient of the smaller machines in the Experimental Engineering Laboratory of Sibley College. It is a double screw machine, power driven. A very wide range of testing speeds is available. The scale on the beam is 1000 pounds per inch, reading to 10 pounds by vernier on the sliding weight. The sector is graduated to pounds. Some years ago the machine was tested for accuracy by loading with dead weights, and was found unusually good. As the weighing apparatus is carried on knife edges, and the machine has always been well kept up, it should now be as accurate as it ever was.

The machine was found subject to one peculiar phenomenon. If the beam was set for a load, say, of 3000 pounds total and run till it floated that, and at the instant the motion cut out, the beam would fall, and to get balance it would be necessary to run back about 175 pounds. Investigation disclosed the fact that this action is zero at 500 pounds total load and thence is directly proportional to the load up to about 12,000 pounds where it becomes practically constant. The "throwback" is also slightly greater with higher speeds of the screws. It reaches at 9000 pounds the rather serious value of 600 pounds. It

was found also that the test-piece shortened as the throwback occurred; whether the shortening was proportional to the throwback was not determined.

The question was how the throwback would affect the tests. The usual method of carrying out such tests is to set the beam for certain predetermined total loads, run to each till the beam floats, then cut out the motion and take the extensometer readings. But under these circumstances, when the extensometer reading is taken the actual load on the piece is about 6 percent less than that which the beam in motion floated; and the extension recorded for the floating load is accordingly 6 percent less than it should be. To get true and accurate results some method must be adopted which will record observations of extension and load which are read simultaneously. The best way is to take the extensions with moving load as the beam picks up the load in motion. The next best way is to stop the machine, and take both load and extension under static load. This is less accurate than taking under motion, but far better than the usual method. Both of these methods, mainly the latter, have been used in these bronze tests; lately all observations have been taken under motion. Under any conditions, the breaking load recorded is necessarily a floating load. Errors of operation and method have always, if possible, been thrown against, not for, the test-pieces.

Before starting tests, the beam was always balanced at zero. There was a small zero drift in the course of a day, so that the possible zero error of load may be put at 10 pounds. While testing, the error of balancing a given load may be also 10 pounds. The net result is a possible error in the total recorded load of 20 pounds, and a probable error of 10. The reciprocal of area of test-pieces was about 7, so that the possible error of reading in pounds per square inch was  $\pm 140$ , and probable error  $\pm 70$ . This work was at least as accurate as ordinary testing machine operation; and the unreasonableness of giving figures in pounds per square inch computed closer than to hundreds is apparent.

The diameters of the test-pieces were measured with a

micrometer to the nearest thousandth of an inch. Due to variable separation of the halves of the mould, the castings had elliptical rather than circular sections, and hence a large and a small diameter were taken and the area computed as an ellipse. Allowing an error of 0.001 inch in each diameter, the possible error in area is one percent, and probably about  $\frac{1}{2}$  of one percent. The net result of all probable errors in area and in load is that the breaking loads computed are in error not more than one percent, even in the worst cases.

Because of the shortness of the bronze pieces an extensometer could not be used. Elongations were taken between prick punch marks at the ends of the cylindrical portion of the test-piece, by very fine pointed dividers (drafting instruments) and lengths read off to thousandths of an inch, using a lens and a flexible steel rule graduated to hundredths. Considerable facility was soon acquired at this, and less than one reading in ten was in error 0.001 of an inch. With a length under observation of 3 inches, the extension per inch is then accurate to 0.00035. The greatest objection to this method of taking extensions is that bending of the test-piece cannot be detected and may introduce errors. The probability of this error being serious is small; the prick punch marks were so placed as to minimize the effect of the bending; and where a test-piece was noticeably bent the data on extensions were either not taken or were taken and not used.

After the breaking of a piece in the testing machine the halves were removed from the jaws and examined. The recorded data of tests<sup>1</sup> tell for each piece whether the fracture showed the piece to be "good" or if not good, what the trouble was—trapped air, oxide, occluded gas, flaw from too cold casting, etc. A piece was considered good if it had the proper color for its composition and the right crystallization if it had stood up well for strength; it was called good even when there were one or two pin points of occluded gas visible.

The typical colors and character of fracture were as follows: The color grades from the familiar red of copper through

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<sup>1</sup> Given in Mr. Upton's thesis but not published in this paper.

red tinted grays to a yellow gray at 92 percent, to pure gray at 84 and 81 percent. Fractures are sometimes cup shaped with 94 or more percent of copper, but are generally, and below 94 percent always square across. From medium sized fibrous in pure copper the material changes gradually to very minutely fibrous in 84 and below, where the surfaces of break are almost smooth planes. From 78 percent down the surface depends on the heat treatment.  $\beta$  shows up in long prismatic needle crystals,  $\delta$  gives a vitreous fracture, light yellow in color. A 75 percent or 70 percent alloy breaks exactly like glass. On cut surfaces the color is decidedly unlike that on fracture. In pure copper it is light yellow, red-tinged. The red is entirely lost at 90 percent or 87 percent; below that the yellow grows whiter, but always remains yellow.

#### IV. Results of tests

It has not seemed desirable to publish all the data obtained. In Table I is given a summary of the final results. The first column shows the heat treatment, *Aqua* being used as an abbreviation for quenched in water. In the second column G (good) denotes that the casting showed no flaws at the fracture, while B (bad) denotes that the casting was imperfect for some reason or other. In the third column the ultimate tensile strength is given in pounds per square inch. In the last column is given the ductility, expressed in percentage elongation. These same

TABLE I.—SUMMARY OF TESTS.

Percentage of copper, 100

Heat treatment		Strength. Pounds per square inch	Ductility. Percent elongation
Tested as cast	G	19650	12.0
Tested as cast	G	17990	—
Tested as cast	G	23740	17.0
Tested as cast	G	19630	22.5
Tested as cast	B	20000	8.0?
Tested as cast	B	15120	7.0?
540° one week, aqua	G	24540	28.0
540° one week, aqua	G	22600	18.5
540° one week, aqua	G	24100	21.5

TABLE I.—SUMMARY OF TESTS—*Continued*

Percentage of copper, 100

Heat treatment		Strength. Pounds per square inch	Ductility. Percent elongation
540° one week, aqua	G	22740	24.5
540° one week, aqua	G	24470	21.5
540° one week, aqua	B	14990	16.0 <sup>1</sup> ?
540° one week, aqua	B	9090	—
540° one week, aqua	B	21580	25.0
Heated to red, aqua	G	25560	28.5
Percentage of copper, 98			
Tested as cast	G	27380	20.0
Tested as cast	G	27700	23.5
540° one week, aqua	G	31670	31.0
540° one week, aqua	B	26940	20.0?
540° one week, aqua	B	24860	15.0?
540° one week, aqua	B	29150	—
540° one week, aqua	B	24780	—
Heated to red, aqua	B	24330	—
Percentage of copper, 96			
Tested as cast	G	31130	20.5
Tested as cast	B	29630	15.0?
540° one week, aqua	G	38000	22.0
540° one week, aqua	G	33460	20.5
540° one week, aqua	G	36600	27.0
540° one week, aqua	B	28830	—
540° one week, aqua	B	24570	—
Heated to red, aqua	G	32140	18.5
Percentage of copper, 94			
Tested as cast	G	32800	8.0
Tested as cast	G	31470	11.0
Tested as cast	G	33440	24.0
Tested as cast	G	37500	18.0
540° one week, aqua	G	34030	24.5
540° one week, aqua	G	32210	24.5
540° one week, aqua	G	34490	16.5
540° one week, aqua	B	24500	5.0?
540° one week, aqua	B	30220	—
540° one week, aqua	B	33000	—
400° one week, furnace-cooled	B	31390	7.0?
400° one week, furnace-cooled	B	28630	8.0?
400° one week, furnace-cooled	B	30630	14.0?
Heated to red, aqua	G	34350	19.5
Heated to red, aqua	G	33760	21.5
Heated to red, aqua	B	30940	—

<sup>1</sup> Broke in grips.

TABLE I.—SUMMARY OF TESTS—(*Continued*)  
Percentage of copper, 92

Heat treatment		Strength. Pounds per square inch	Ductility. Percent elongation
Tested as cast	G	41020	11.5
Tested as cast	B	23230	—
Tested as cast	B	27620	—
Tested as cast	B	24560	—
540° one week, aqua	G	32990	33.0
540° one week, aqua	G	38870	22.5
540° one week, aqua	G	31930	18.5
540° one week, aqua	G	39110	28.5
540° one week, aqua	G	34470	23.0
540° one week, aqua	B	27720	—
540° one week, aqua	B	29560	14.0?
540° one week, aqua	B	24800	—
540° one week, aqua	B	29830	—
540° one week, aqua	B	34930	18.0?
540° one week, aqua	B	30000?	—
540° one week, aqua	B	33440	—
Heated to red, aqua	G	39190	21.0
Heated to red, aqua	G	34440	20.0
Heated to red, aqua	B	36510	—
Percentage of copper, 90			
Tested as cast	G	44580	17.0
Tested as cast	G	44280	12.0
Tested as cast	G	40140	9.0
Tested as cast	B	30830	6.0?
Tested as cast	B	31040	10.0?
Tested as cast	B	32090	10.0?
Tested as cast	B	30420	5.0?
540° one week, aqua	G	46920	47.5
540° one week, aqua	G	42900	35.0
540° one week, aqua	G	45790	37.5
540° one week, aqua	G	37240	25.5
540° one week, aqua	B	35630	20.0?
540° one week, aqua	B	34580	20.0?
540° one week, aqua	B	30390	—
540° one week, aqua	B	33080	25.0?
540° one week, aqua	B	26180	—
540° one week, aqua	B	20440	—
400° one week, furnace-cooled	G	40040	26.0
400° one week, furnace-cooled	G	39120	19.5
400° one week, furnace-cooled	G	43130	28.5
Heated to red, aqua	G	44670	21.0
Heated to red, aqua	B	34570	—

TABLE I.—SUMMARY OF TESTS—(Continued)  
Percentage of copper, 90

Heat treatment		Strength. Pounds per square inch	Ductility. Percent elongation
Heated to red, aqua	B	38220	—
Brought to 630°, aqua	B	27830	—
Brought to 620°, aqua	B	30590	—
Brought to 630°, aqua	B	28080	—
Percentage of copper, 87			
Tested as cast	G	46430	8.5
Tested as cast	G	38130	4.5
Tested as cast	G	32950	4.0
Tested as cast	G	46440	5.0
Tested as cast	G	42840	3.5
Tested as cast	G	42080	6.0
Tested as cast	G	39600	4.5
Tested as cast	B	35640	—
Tested as cast	B	37940	—
Tested as cast	B	37280	—
540° one week, aqua	G	42000	26.5
540° one week, aqua	G	48200	39.0
540° one week, aqua	B	32080	—
540° one week, aqua	B	29500	—
540° one week, aqua	B	29310	—
540° one week, aqua	B	25210	—
540° one week, aqua	B	38180	—
540° one week, aqua	B	36230	—
540° one week, aqua	B	36320	—
540° one week, aqua	B	24970	—
400° one week, furnace-cooled	G	37530	8.5
400° one week, furnace-cooled	G	38770	11.5
400° one week, furnace-cooled	B	35670	12.0?
Heated to red, aqua	G	44080	7.0
Heated to red, aqua	G	39740	9.5
Heated to red, aqua	B	41790	7.0?
Brought to 620°, aqua	G	47370	17.5
Percentage of copper, 84			
Tested as cast	G	35210	1.0
Tested as cast	G	35930	1.3
Tested as cast	G	36140	1.7
Tested as cast	G	50760	2.0
Tested as cast	G	39900	—
Tested as cast	B	29080	1.0?
Tested as cast	B	43800	1.0?
540° one week, aqua	G	38570	16.0

TABLE I.—SUMMARY OF TESTS—(*Continued*)

Percentage of copper, 84

Heat treatment		Strength. Pounds per square inch	Ductility. Percent elongation
540° one week, aqua	G	37400	19.0
540° one week, aqua	G	52250	—
540° one week, aqua	G	43990	20.5
540° one week, aqua	G	58030	20.5
540° one week, aqua	G	51410	—
540° one week, aqua	G	56170	17.7
540° one week, aqua	G	58700	21.5
540° one week, aqua	G	56710	22.0
540° one week, aqua	B	35520	1.0?
540° one week, aqua	B	46030	—
540° one week, aqua	B	43860	—
540° one week, aqua	B	46240	—
400° one week, furnace-cooled	G	45740	2.0
400° one week, furnace-cooled	G	43430	1.4
400° one week, furnace-cooled	G	32720	2.5
Heated to red, aqua	G	57220	8.0
Heated to red, aqua	G	60680	11.0
Heated to red, aqua	B	58220	—
Brought to 620°, aqua	G	56300	11.0
Brought to 620°, aqua	G	52680	7.0

Percentage of copper, 81

Tested as cast	G	54140	2.9
Tested as cast	G	53200	—
Tested as cast	B	20830	—
540° one week, aqua	G	49940	—
540° one week, aqua	G	49360	—
540° one week, aqua	G	48360	—
540° one week, aqua	G	60960	—
540° one week, aqua	G	61650	—
540° one week, aqua	G	60260	—
540° one week, aqua	B	48160	5.0?
540° one week, aqua	B	38300	—
400° one week, furnace-cooled	G	42200	0.4
400° one week, furnace-cooled	G	33000	—
400° one week, furnace-cooled	G	41260	0.6
400° one week, furnace-cooled	G	45900	0.6
400° one week, furnace-cooled	B	31200	—
400° one week, furnace-cooled	B	37500	0.5?
400° one week, furnace-cooled	B	32500	0.5?
Heated to red, aqua	G	65750	7.3
Heated to red, aqua	G	61720	8.0



TABLE I.—SUMMARY OF TESTS—(Continued)

Percentage of copper, 81

Heat treatment		Strength. Pounds per square inch	Ductility. Percent elongation
Heated to red, aqua	G	60670	3.5
Brought to 620°, aqua	G	61320	—
Brought to 620°, aqua	G	72340	6.5
Cast, air-cooled	G	37430	0.3
Cast, air-cooled. Cast, cold	G	32740	0.2
720° three-fourths hour, aqua	G	68630	6.5
720° three-fourths hour, aqua	G	61480	5.0

Percentage of copper, 78

Tested as cast	G	39520	0.35
Tested as cast	G	49260	—
Tested as cast	B	41150	—
Tested as cast	B	23750	—
Tested as cast	B	36110	—
540° one week, aqua	G	55530	—
540° one week, aqua	G	62930	—
540° one week, aqua	G	51950	—
540° one week, aqua	G	52200	—
540° one week, aqua	B	10000?	—
400° one week, furnace-cooled	G	23980	—
400° one week, furnace-cooled	G	29380	—
400° one week, furnace-cooled	G	21780	—
400° one week, furnace-cooled	B	27910	—
Heated to red, aqua	G	67600	1.3
Heated to red, aqua	G	58940	1.2
600°-620° one hour, aqua	G	56750	4.0
600°-620° one hour, aqua	G	49880	—
600°-620° one hour, aqua	G	64170	6.6
Brought to 700° and air-cooled	G	17630	0.05
Brought to 700° and air-cooled	B	15080	—
700° three-fourths hour, aqua	G	52240	0.6
700° three-fourths hour, aqua	G	52260	0.5
700° three-fourths hour, aqua	G	60400	1.2
400° one hour, air-cooled	B?	14260	} <sup>1</sup>
400° one hour, air-cooled	B	16970	
400° one hour, air-cooled	B	5450	
Brought to 700°, aqua	G	51350	1.6
Brought to 700°, aqua	G	56260	—
Brought to 700°, aqua	G	62720	—

<sup>1</sup> All developed large cracks in cooling.

TABLE I.—SUMMARY OF TESTS—(*Continued*)

Percentage of copper, 75

Heat treatment		Strength. Pounds per square inch	Ductility. Percent elongation
Tested as cast	G	10390	0
Tested as cast	G	16810	—
Tested as cast	G	15180	—
Tested as cast	B	6510	—
540° one week, aqua	G	34060	—
540° one week, aqua	G	30870	—
540° one week, aqua	G	10730	—
400° one week, furnace-cooled	G	22340	—
400° one week, furnace-cooled	G	15490	—
400° one week, furnace-cooled	G	14190	—
400° one week, furnace-cooled	B	6900	—
630° one hour, aqua	G	35640	1.1
630° one hour, aqua	G	27450	0.4
600° one hour, aqua	G	36730	0.35
700° one hour, aqua	G	27860	0.3
700° one hour, aqua	G	34970	0.75
700° one hour, aqua	G	38730	2.1

Percentage of copper, 70

Tested as cast	G	0	— <sup>1</sup>
Tested as cast	G	15780	—
Tested as cast	B	3320	—
400° one week, furnace-cooled	G	3490	—
400° one week, furnace-cooled	B	0	— } <sup>2</sup>
400° one week, furnace-cooled	B	0	— }

results are given in a more condensed form in Table II only the sound castings being included.

<sup>1</sup> Broke while being placed in jaws.<sup>2</sup> Broke while being gripped.

TABLE II.—STRENGTHS AND DUCTILITIES OF “GOOD” PIECES IN REGULAR SERIES.

	540°, 1 week, Aqua		Tested as cast		400° 1 week furnace cooled		Brought to red, Aqua	
	Ultimate		Ultimate		Ultimate		Ultimate	
Cu percent	Strength lbs/sq in	Elonga- tion percent	Strength lbs/sq in	Elonga- tion percent	Strength lbs/sq in	Elonga- tion percent	Strength lbs/sq in	Elonga- tion percent
100	24500	28.0	19600	12.0			25600	28.5
	22600	18.5	23700	17.0				
	24100	21.5	19500	22.5				
	22700	24.5	18000					
	24500	21.5						
98	31700	31.0	27400	20.0				
			27700	23.5				
			31100	20.5			32100	18.5
96	38000	22.0						
	33500	20.5						
	36600	27.0						
94	34500	16.5	32800	8.0			34400	19.5
	34000	25.5	31500	11.0			33800	21.5
	32200	24.5	33400	24.0				
			37500	18.0				
			41000	11.5			39200	21.0
92	33000	33.0					34400	20.0
	38900	22.5						
	31900	18.5						
	39100	28.5						
	34500	23.0						
90	46900	47.5	44600	17.0	40000	26.0	44700	21.0
	42900	35.0	44300	12.0	39100	19.5		
	45800	37.5	40100	9.0	43100	28.5		
	37200	25.5						
	48200	39.0	46400	8.5	37500	8.5	44100	7.0
87	42000	26.3	32900	4.0	38800	11.5	39700	9.+
			38100	4.5				
			39600	4.5				
			42100	6.0				
			42900	3.5				
			46400	5.0				
	52200	—						
	38600	16.0	35200	1.0	45700	2.0	57200	8.0
	56200	17.7	35900	1.3	43400	1.4	60700	11.0
	37400	18.0	36100	1.7	32700	2.5		

TABLE II.—STRENGTHS AND DUCTILITIES OF "GOOD" PIECES IN REGULAR SERIES

	540°, 1 week, Aqua		Tested as cast		400° 1 week furnace cooled		Brought to red, Aqua	
	Ultimate		Ultimate		Ultimate		Ultimate	
Cu percent	Strength lbs/sq in	Elonga- tion percent	Strength lbs/sq in	Elonga- tion percent	Strength lbs/sq in	Elonga- tion percent	Strength lbs/sq in	Elonga- tion percent
84	58700	21.5	50800	2.0				
	44000	20.5	39900	—				
	56700	22.0						
	58000	20.5						
	51410	—						
	49900	—						
	61000	—						
	49400	4.3	54100	2.9	42200	0.4	65700	7.3
81	48400	3.2	53200	—	41300	0.6	61700	8.0
	60200	4.3			45900	0.6	60700	3.5
	55500	—	39400	0.35	24000	—	67600	1.3
	62900	—	49300	—	29400	—	58900	1.2
78	51900	—			21800	—		
	52200	—						
75	34000	—	10400	0.0	22300	—		
	30900	—	16800	—	15500	—		
	10700	—	15200	—	14200	—		
70			0	—	0	—		
			15800	—	3500	—		

The curves for the tensile strengths are plotted in Fig. 4, the abscissas being percentages of copper and the ordinates pounds per square inch. Until we reach 87 percent copper, there is practically no effect due to heat treatment. This was to be expected because the bronzes richer in copper are homogeneous  $\alpha$ -crystals and have no inversion-point. The difference between the test-pieces would, therefore, be due primarily to size of crystals and to possible strains. From 87 percent down to 76 percent copper we get marked differences due to heat treatment. The alloys which have been held at 400° (curve D in Fig. 4) are below the inversion temperature and consist of a mixture of  $\alpha$  and  $\delta$  crystals, while the alloys which have been

held at  $540^{\circ}$  or which have been heated to low red (curves B and A in Fig. 4) are above the inversion-point and consist of a mixture of  $\alpha$ - and  $\beta$ -crystals. These alloys are much stronger than the preceding set, a breaking strength of 67,000 pounds per square inch having been obtained with a 78 percent bronze consisting of  $\alpha$ - and  $\beta$ -crystals, while about 45,000 pounds is the maximum for a bronze consisting of  $\alpha$ - and  $\delta$ -crystals. The 78 percent bronze brings out the effect of heat treatment very markedly, the tensile strength being well over 60,000 pounds

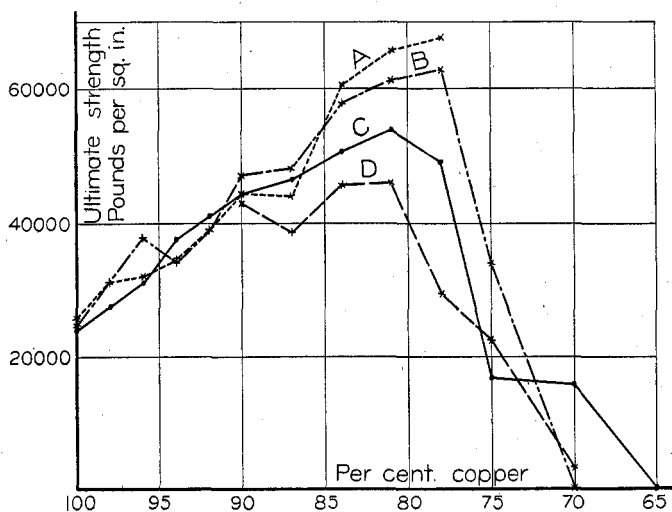


Fig. 4

- A. Heated to low red, water-quenched.
- B. Held one week at  $540^{\circ}$ , water-quenched.
- C. Tested as cast.
- D. Held one week at  $400^{\circ}$ , furnace-cooled.

for a bronze quenched from above the inversion temperature and only 30,000 pounds for a bronze annealed below this temperature. The differences between the bronzes which have been held fifteen minutes at a low red and those which have been held a week at  $540^{\circ}$  are undoubtedly due to a coarser crystallization in the latter.

Between 86 percent and 76 percent copper, the curve for the bronzes as cast, lies between those for bronzes annealed above

and below the inversion temperature. This was to be expected because the cooling was too rapid to permit a complete change into the  $\delta$  crystals and yet not rapid enough to prevent any change. These bronzes are, therefore, a mixture of  $\alpha$ -,  $\beta$ - and  $\delta$ -crystals.

Since a bronze containing  $\alpha$ - and  $\beta$ -crystals is much stronger than one consisting of  $\alpha$ -crystals alone, it might reasonably have been expected that pure  $\beta$  would give us the strongest of the copper-tin bronzes. This is not the case experimentally and the maximum strength occurs at 77-78 percent copper<sup>1</sup> which is about the maximum content for pure  $\beta$  at any temperature though well above the maximum content of pure  $\beta$  at the temperatures of the experiments. Why this should be so, cannot be explained until we have more data on other and simpler alloys. As the copper content falls below 77 percent there is a rapid decrease in the strength of the bronzes annealed above the inversion-point. The alloy with 70 percent copper has practically no strength whether annealed above or below 500°. Of two 70 percent bronzes tested as cast, one broke while being placed in the jaws of the testing-machine while the other had a tensile strength of nearly 16,000 pounds per square inch. Such a bronze may contain  $\alpha$ ,  $\beta$ ,  $\gamma$  and  $\delta$  crystals in varying amounts depending on the rate of cooling. It is, therefore, entirely uncertain what the actual composition or properties of any given casting might be.

In the bronzes annealed at 400° the first admixture seems to have no effect on the strength. As soon as the  $\delta$  crystals become more than 30 percent of the whole, the strength decreases rapidly.

Some comparisons with the results of previous investigations on the strengths of cast bronzes, unworked, may be made. The only investigations covering the same wide range of compositions are by Mallet<sup>2</sup> and by Thurston<sup>3</sup>. Their results, with those of the present investigation (called Shepherd-Upton on the curve) are given in Fig. 5. Mallet's strength of pure copper

<sup>1</sup> One 81 percent bronze gave 72,000 pounds when quenched from 620°.

<sup>2</sup> Phil. Mag. 21, 66 (1842.)

<sup>3</sup> Report on the Properties of Copper-Tin Alloys. Washington, 1879.

was undoubtedly taken from a test on a wire and is therefore not comparable. His results for castings agree well with those of Thurston. The Shepherd-Upton curve is curve C from Fig. 4 and represents the results as obtained from pieces as cast without any heat treatment. The differences between the Shepherd-Upton curve and the Thurston curve are very marked for bronzes containing less than 96 percent copper. In fact Thurston's curve lies below that of the authors for bronzes annealed at  $400^{\circ}$ . The slow cooling in Thurston's castings evidently gave time for a complete change of the  $\beta$  phase into the  $\delta$  phase. In addition Thurston's castings were by no means sound. Thurston wished to get the commercial strengths and

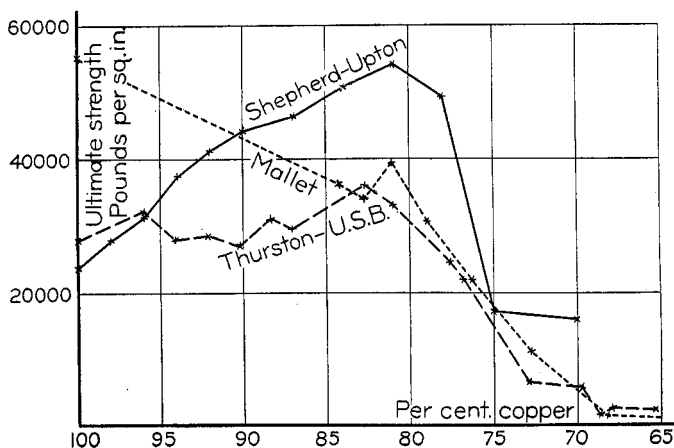


Fig. 5

therefore employed a brass founder, who used the current practice of that time in the melting and pouring of the metal. Practice has since changed somewhat for the better. The Shepherd-Upton curve was made with the deliberate idea of finding the maximum value and any commercial practice that interfered with obtaining such a result was either discarded or changed. That does not make the results "laboratory" strengths. The methods and means used can all be applied commercially either directly or in modified form. An instance of this is the centrifugal sprew and air-trap combination.

Another instance is the well-known high strength of phosphor bronze. As usually used, it is doubtful whether any phosphorus is left in the final casting. The part it plays is the prevention of oxidation and of occluded gases. If more than enough phosphorus for this purpose is used, the alloy becomes weaker and so brittle as to be useless.

In Fig. 6 are plotted the tests on ductility, the abscissas being percentage copper and the ordinates percentage elongation. In these results the time factor is a very important one. While increased size of crystal is a disadvantage as far as the strength is considered, it appears to be favorable to ductility, pre-

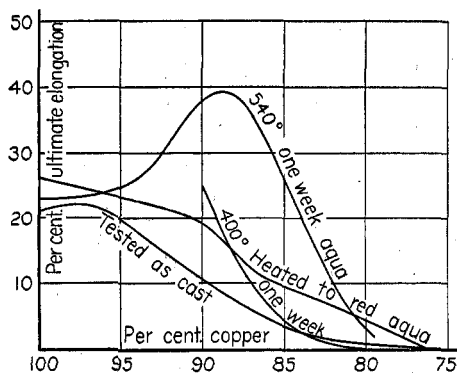


Fig. 6

sumably because the crystals slip more readily. In the bronzes as cast there is a slight maximum of ductility at about 97.5 per cent copper which probably means nothing. Except for this the ductility decreases with decreasing copper content. The bronzes that have been held fifteen minutes at a dull red and then quenched show a decreasing ductility with decreasing copper content. Down to 80 per cent copper the ductility is approximately 5 percent higher than in the cast bronzes. When the bronzes are held for a week at 540° and then quenched we get a most remarkable curve. There is a maximum ductility at about 88-90 per cent copper, very close to the limiting maximum concentration of the  $\alpha$ -crystals. This maximum ductility repre-



sents in round numbers a 39 percent elongation.<sup>1</sup> So far as we can see, this can only be due to a change in the size of the crystals, since the tensile strength experiments showed that equilibrium was reached in fifteen minutes at a low red heat, about 650°.

The ductility of the bronzes annealed for one week at 400° does not differ appreciably from that of the cast bronzes so long as we have a mixture of the two crystals,  $\alpha$  and  $\delta$ . As soon as the copper content exceeds 85 percent the ductility of the bronzes annealed at 400° increases very rapidly cutting the curve for the bronzes quenched from a low red at 88 percent copper. The experiments were not carried beyond 90 percent copper because the tensile strength of a bronze containing 90 percent and upward of copper is practically independent of the heat treatment. Since the 88 percent bronze consists of pure  $\alpha$  both at 400° and at 540°, the two must have the same ductility, giving the same size of crystals. It seems reasonably certain that the reason for the difference between the two is merely a difference in the rate of growth of the crystals. If the 88 percent bronze had been held two, three, or, if necessary, four weeks at 400°, it would eventually have shown the same ductility as the same bronze held for one week at 540°.

In Fig. 7 are given stress-strain curves for 100 percent copper, for a bronze containing 90 percent copper, for a bronze containing 81 percent copper and two for ordinary wrought iron. The ordinates are percentage elongations with a special zero for each metal. The abscissas are pounds per square inch. The numbers at the ends of the curves give the ultimate percentage elongation. Whatever the composition or heat treatment the copper and the bronze curves do not lose their similarity in shape. They have no elastic line or limit. A yield point might be arbitrarily selected, but its location would depend almost entirely on the horizontal scale to which the curve was drawn. Indeed a yield point is in general hard to place at all. The bronzes have no maximum load in the sense that iron and

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<sup>1</sup> One 90 percent bronze gave 47 percent.

steel do. A bronze runs up to its break without the curve ever turning over.

When considering the shape of the curve it must be kept in mind that these are tests of cast bronzes and that the pieces had never previously been under load or worked in any way. Working the metal would have made it have an elastic line because it would have been strained. With bronzes containing 87 percent to 92 percent copper, it should be possible to get a large increase of strength by cold working. If in testing one of these cast bronzes the load be run up to one-half or two-thirds of the ultimate strength and then removed, a set line is found; only

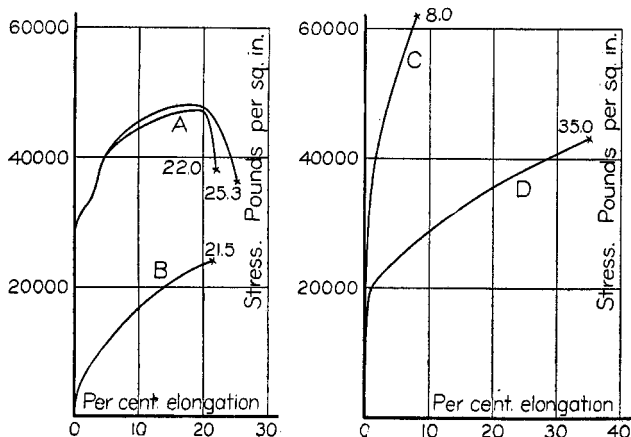


Fig. 7

- A. Wrought iron.
- B. Copper—100; 540° one week, aqua.
- C. Copper—90, tin—10; 540° one week, aqua.
- D. Copper—81, tin—19; heated to red, aqua.

from such lines can the modulus of elasticity be derived. Connected with this is the interesting phenomenon that some of the test-pieces can easily be bent nearly double by hand; but it is quite impossible to bend them back again.

The ultimate resilience of bronzes containing more than 95 percent copper is low because the breaking strengths are low. With bronzes containing less than 85 percent copper, the resilience is low because the elongation is small. The maximum resilience occurs between 90 percent and 87 percent copper; it is

some 15 percent higher than that of the wrought iron curve.

The results of this paper may be summed up as follows :

1. A study has been made of the effect of heat treatment on the tensile strength and ductility of cast copper-tin alloys containing more than 70 percent copper.

2. The tensile strength of bronzes consisting of pure  $\alpha$  is affected but slightly by heat treatment.

3. Bronzes containing 74-87 percent copper are much stronger if annealed above the inversion temperature ( $510^{\circ}$ ) than if annealed below.

4. Prolonged annealing tends to coarsen the crystalline structure, to decrease the tensile strength, and to increase the ductility.

5. The tin-rich  $\alpha$  crystals are stronger than those low in tin.

6. The strongest bronzes contain 78-81 percent copper and are mixtures of  $\alpha$  and  $\beta$  crystals.

7. The strongest of the bronzes annealed below  $510^{\circ}$  consist of mixtures of  $\alpha$  and  $\delta$  crystals.

8. Bronzes containing no  $\alpha$  crystals have very low tensile strengths.

9. When tested as cast, the ductility of bronzes decreases with decreasing copper content.

10. The ductility of cast bronzes can be increased about 5 percent by bringing to a red heat and then quenching in water. With bronzes containing less than 88 percent copper, this treatment increases the strength markedly.

11. Annealing at  $540^{\circ}$  for one week causes an enormous increase in the ductility especially of bronzes containing 88-90 per cent copper.

12. Annealing the 85-90 percent Cu bronzes at  $400^{\circ}$  for one week causes an effect on ductility similar to, but less than that due to annealing for the same time at  $540^{\circ}$ .

13. It is possible to make a cast bronze with an ultimate tensile strength of over 60,000 pounds per square inch and an ultimate elongation of about 1.5 percent or a bronze with an ultimate tensile strength of 45,000 pounds per square inch and an ultimate elongation of 39 percent.

14. By suitable heat treatment it is possible to vary the ultimate elongation of a bronze containing 90 percent copper from 10 percent to 37 percent without affecting the tensile strength materially.

15. The bronzes have no maximum load in the sense that iron and steel do.

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*Cornell University, January, 1905.*