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ON THE STRUCTURE OF CAST-STEEL INGOTS.

BY D. CHERNOFF.

(Read before the Imperial Russian Technical Society, 2nd December, 1878.)

TRANSLATED BY MR. WILLIAM ANDERSON, OF ERITH,
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Among the materials necessary for the successful prosecution of the various arts at the present time, the foremost place is occupied by iron, taken in all its varieties, as wrought-iron, steel, and cast iron.

So long as the metallurgical art was incapable of producing steel in large masses and at a cheap rate, the wants of the engineer and mechanic were chiefly supplied by cast and wrought iron. The methods of working these two forms of the metal differed essentially from each other. The high melting point of wrought iron, and the imperfect means of fusion at the disposal of the metallurgist, obliged the required shapes to be given by means of welding, forging, and rolling, thus necessitating the use of large quantities of fuel, and the employment of powerful machinery. The comparatively low melting point of cast iron permits the difficult work of shaping the metal to be transferred to the moulding of such soft substances as wood, clay, or sand. To obtain the most complicated shapes, it is only necessary to make a pattern out of wood, clay, &c., mould it in friable sand, and run into the impression so produced the molten metal, which at once assumes the required shape and dimensions. The mechanical labour to be afterwards expended is limited to finishing the surfaces, if required; but the greater number of castings either require no finishing at all, or are only surfaced in isolated places. The convenience of this method of producing ironwork is so great, that it is adopted in every department of constructive or decorative art, if the nature of the materials used will permit.

As soon as the iron industry became possessed of the means of obtaining, in the fluid state, steel of any desired quality, in large masses and at a cheap rate, the direct consequence of such progress should naturally have been the adaptation of the founder's art to the production of every kind of article in cast steel. But the numerous attempts to apply to steel the ordinary methods of casting, in sand or metallic moulds, were far from being crowned with success, especially with the milder qualities. The chief defect was the prevalence of a honey-combed structure, due partly to gas-bubbles, partly to cavities caused by contraction in cooling. Occasionally the external cracks which were developed, and even the texture of the steel itself, made it useless for practical purposes. For this reason it is that steel-founders, for the most part, content themselves with producing masses of the simplest form, or else ingots, which are afterwards worked into the required shape by forging or other mechanical means, and at an enormous cost for fuel.

However great may be the difficulties in attaining the object thus sought for, it is impossible to desist from its pertinacious pursuit, in view of the immense advantages which accrue from the facilities offered by the process of casting. And as victory in the struggle with an evil of any kind can be ensured only by carefully studying that evil, it is easy to see what importance attaches to an investigation into the defects of cast-steel ingots.

To begin with, we may take the simplest form, that of a cylindrical ingot cast in a metallic mould. Fig. 1, Plate 7, represents a longitudinal section of such an ingot, about one-tenth full size. Instead of a solid mass, it appears as a casting permeated by a large number of cavities. Along the external surface, and in contact with the mould, numerous bubbles penetrate into the body of the ingot, more or less deeply according to the circumstances under which it was cast and the quality of the steel used, and give to the external layer a spongy appearance, as illustrated on the upper side of Fig. 1. In what was the upper end of the ingot a large cavity, having the shape of an irregular funnel, has been formed. This cavity penetrates deeply along the axis of the casting, and is surrounded by unsound metal,

permeated by small cavities or bubbles. It descends along the axis of the ingot far below the apex of the cone, and forms, in places, hollows of considerable size. Following a direction receding radially from the central axis of the casting, the porosity diminishes, and becomes, at last, imperceptible to the eye; so that a certain thickness of metal, included between the spongy crust and the porous heart, appears to be sound and compact.

Under certain circumstances, to which further allusion will be made, bubbles are not formed, or at any rate in a very slight degree only, at the outer surfaces of ingots cast in metallic moulds; but instead a strongly-marked acicular, or needle-like, structure becomes apparent, as illustrated on the lower side of Fig. 1.

An examination of the fractured surface shows that the acicular layer consists of a conglomeration of irregular prismoidal bodies, arranged at right angles to the sides of the ingot, as shown full size in Fig. 2. The cohesion between the prismoids is not great, so that ingots having this structure break up with comparative ease, fracture taking place along the facets of the prisms and presenting a dead silvery hue.

Within the acicular layer comes a more or less pronounced granular structure, composed of irregular many-sided grains, as shown two-thirds full size in Fig. 3, having a dead silvery colour very similar to that characterising the surfaces of the prismoids. Within this layer comes the compact metal, having a brilliant solid fracture; and then follows the porous portion, which becomes more open as the core of the casting is approached.

Each of the above-named defects requires to be examined in turn.

The imperfection, the origin of which is most easily explained, is the funnel-shaped cavity in the upper end of the ingot, caused by the setting of the metal. The solidification, hastened by the cooling influence of the sides of the mould, necessarily takes place in layers following its inner surface. According as the layers grow thicker the level of the liquid sinks, because the volume of the metal decreases and gives room to the still fluid central column, which, as it falls, also constantly diminishes in diameter at its upper surface.

The phenomenon described is so well known and understood by founders that it is unnecessary to dwell further upon it.

The bubbles permeating the outer surface of an ingot present one of the most important defects met with in steel castings, and have long been the subject of enquiry by many metallurgists. With respect to the origin of the gases occluded in fluid steel, it cannot be said that any unanimity of opinion exists among those who have investigated the matter. Some, for example, are inclined to attribute the presence of gases simply to the solution of the products of combustion of the furnace in the fluid steel, during the time it is melting; others hold the opinion that they are merely the products of chemical reaction, taking place between the elements constituting the fluid steel, and the substances forming the linings of the furnaces and of the ladles used; others again ascribe the formation of the gases to the reactions which take place between the elements composing the fluid steel, under the influence of oxygen derived from the products of combustion or from the atmosphere.

It is unnecessary to examine critically these conflicting opinions: each of them is based on factitious data, and cannot be authoritatively proved erroneous. It should however be added that each of the above-mentioned causes contributes, together with the rest, in generating gases; which thus appear to be the result of their combined and simultaneous operation.

The ordinary view, which has not been controverted, is that the great bulk of the gases produced is composed of carbonic oxide;* and it is very generally allowed that the period at which the largest quantity of gas is formed is at the point of transition from the fluid

* Within the last year Müller has stated (*Berichte der deutschen chemischen Gesellschaft*, 1879, No. 1) that analyses of the gases from the pores in steel castings have yielded from 60 to 90 per cent. of hydrogen, the remainder of the gas being nitrogen, with only a small quantity of carbonic oxide. If these results are confirmed by more extended observation, they will open an entirely new field of speculation in the metallurgy of steel.

to the solid state. On considering this phenomenon more closely, it is easy to see that it is subject to the laws which govern the solution of gases in other liquids. In fluid steel, as well as in other liquids saturated with gas, the greatest evolution takes place when the mass is agitated, or especially when the liquid is poured from one vessel into another. Accordingly, in pouring steel from the Bessemer converter into a ladle, or from the ladle into the mould, violent ebullition, with a copious evolution of gases, takes place. If there were no risk in cooling the steel, and if it could be protected from the action of the oxygen in the air, a succession of pourings would be sufficient to remove the whole of the imprisoned gases.

Steel cast into a mould, and allowed to cool, immediately commences to evolve gas in the form of very minute bubbles, which adhere to the first particles of steel solidified against the sides of the mould. In consequence of the property possessed by dissolved gases, of escaping into space or into bands of already existing bubbles, the bubbles which have fixed themselves to the first portions of solidified steel grow rapidly by the influx of gases from the metal surrounding them. Inasmuch as the thickness of the solidified layer is always increasing, in consequence of the cooling influence of the sides of the mould, the augmentation in volume of the bubbles must occur exclusively, or nearly so, in a direction perpendicular to the sides. In this way the form of a bubble may vary in accordance with the varying rate at which the bubble grows in volume, compared with that at which the thickness of the solid layer increases. If the bulk of the bubble increases more rapidly than the thickness of the solid layer increases, then the diameter of the bubble becomes greater as it recedes from the sides; and it assumes the shape of a cone with a spherical end, the larger diameter being turned towards the centre of the ingot (Fig. 4, Plate 8). When the gases, under these circumstances, collect too rapidly, the enlarged portions of the bubbles grow very quickly, and are from time to time torn off and float to the surface. If the growth of the bubbles coincides with the rate of thickening of the solidified metal, then the bubbles become of a cylindrical form with a hemispherical termination (Fig. 5).

Finally, if the setting of the steel goes on more quickly than the accumulation of gas, then the bubbles gradually taper away inwards to a point (Fig. 6); bubbles of this last character however are extremely rare.

As the mould fills, the pressure of the fluid column on the lower layers of steel continually increases, and, at the same time, the facility with which the gases separate from the metal decreases; consequently the further development of the bubbles in the lower layers is arrested. The bubbles become sealed in, and the subsequently formed layers solidify free from bubbles, unless a fresh evolution takes place from an accidental reduction of pressure. When a bubble becomes thus sealed up, a contraction-cavity is formed at its apex; the interior of this cavity is lined with crystals, to which particular attention will be directed later on.

From the foregoing it is evident that, if it were possible to arrest the formation of the original minute bubbles, which affix themselves to those particles of steel which first set on the sides of the mould, the solidifying surface of the ingot would not then be permeated by the ever-growing bubble cavities. The bubbles that would form, having no attachment to the sides, would float up readily to the top, and leave the surface of the casting perfectly solid.

The phenomenon of the adhesion of particles of steel to the walls of the mould is analogous to the wetting, by water, of the sides of a vessel. The hotter the steel, the less the sides of the mould are wetted as the metal is poured in; and on the other hand the more refractory and impermeable to heat are the materials forming the mould, the less are the chances of their sides being wetted, and of particles of solidified steel sticking to them. From these considerations it may be concluded, (1) that hot steel, which will not wet the sides of a metallic mould, will yield castings free from bubbles in their outer surfaces; and (2) that steel hot enough not to wet the sides of a sand mould, while cool enough to wet those of a metallic mould, will give sound castings in the former case and porous castings in the latter.

Experience quite justifies these conclusions: very hot steel does give a sound casting, even in a metallic mould; and does so, as a

matter of course, in a well dried and warmed sand mould, the exception being only those places which have been splashed by the metal in pouring; to these the steel has in fact adhered, and they are therefore easily wetted. An extremely interesting experiment, which has been frequently repeated, namely that of pouring moderately hot steel into a mould half metallic and half lined with sand, always gave ingots porous on the side in contact with the metallic mould, and perfectly sound on the side next to the ganister lining. Fig. 7, Plate 8, represents an actual section of such an ingot, reduced to one-eighth its natural size.

What has hitherto been said as to bubbles has reference to the period of filling the mould with steel, and to the first moments after casting; during which time the gases can easily escape into the atmosphere, partly through the free uncovered upper surface of the metal, and partly by means of the bubbles which float up and burst there. As soon as the upper surface begins to be covered by a solidified layer, the free escape of gases becomes more difficult, while their solubility decreases* in consequence of the lowering of the temperature to the congealing point; the gases then collect under the top crust, acquire considerable tension, and by that means arrest the further formation of bubbles even in the highest layers of the ingot; while those previously formed become locked up in the solidified outer layers, and thus further evolution of gas is almost completely checked. If however the top crust happens to be weak, then the collected gases burst through it, and the partially set steel, in the form of a foamy mass, breaks through with them; the pressure is thus suddenly relieved, and a fresh evolution of gas takes place, accompanied by the formation of a second row of bubbles, chiefly in the upper portions of the casting.

The points to which this second row of bubbles becomes attached are the imperfectly closed contraction-cavities of the first row; this

* Although, according to the law of the dissolution of permanent gases in liquids, their solubility increases with the fall of temperature of the liquid, yet this law only holds down to temperatures more or less above the temperature of congelation, and does not therefore apply to the case in point.

explains the existence of a sharp line of demarcation between the bands containing the first and the second line of bubbles, as may be seen in Fig. 8, Plate 8, where the right-hand boundary of the shaded portion is that between the liquid and the solid metal, at the moment of the reduction of pressure caused by the rupture of the upper crust of the ingot.* For greater distinctness this is drawn on an enlarged scale.

But notwithstanding the circumstances which have just been described, the evolution of gases, even beneath an unbroken crust, does not altogether cease until the solidification of the very last particles of steel in the centre of the ingot has taken place. The cause of this persistent evolution is the reduction of the pressure in the gases collected under the upper crust, partly from the gradual cooling of the mass, and partly from the increased space afforded by the growth in volume of the contraction-cavities. These circumstances explain the reason why the upper portions of steel castings are permeated by so many bubble-shaped cavities.

These defects occur even in compressed steel. Figs. 9, 10, and 11, Plate 9, which represent a compressed steel ingot $21\frac{1}{2}$ in. diameter, 5 ft. 7 in. long, and weighing 3 tons, illustrate clearly that if the pressure ceases before the central portions of the castings have set, the evolution of gases commences in the still fluid portions: the reason being that the reduction of bulk in the metal causes a partial vacuum, and so draws out the gases. The same thing occurs, even under prolonged pressure, if this is not sufficiently intense, in which case the plunger cannot follow the shrinkage of the steel, but is arrested in its motion by the solidification of the outer portions of the casting. The ingot represented in Plate 9 was pressed for three quarters of an hour; while it has since been ascertained that one hour and a quarter is necessary to produce sound work.

The internal surfaces of the bubble-shaped cavities generally present a clean silvery appearance. But as the side bubbles have

* In order to hasten the formation of an upper crust on the ingots, they are either covered, immediately after pouring, by a cold iron plate, or have water poured on them.

their origin very close to the outside surface of the ingot, and are only divided from the atmosphere by thin diaphragms, it often happens that these are either broken or rusted through during the cooling of the ingot; and, communication being thus made between the cavities and the air, the sides of the cavities become covered with scale, or assume iridescent colours, according as the air has more or less freedom of access. The upper funnel-shaped contraction-cavity has also an oxidised surface, because the rupture of the crust covering it, before it finally sets, allows the access of air to its interior.

The next point for consideration is the setting of the interior liquid steel, and the growth of the solid layers from the external surface to the centre of the ingot.

On examining the sides of the contraction-cavities, it will be noticed that they are covered by minute crystalline growths, formed by the piling up on one another of steel crystals. The accumulation of such growths in the funnel-shaped contraction-cavity, and especially at its lower end, forms a porous mass in which considerable cavities frequently occur. The general appearance of the lower part of the funnel is illustrated full size in Fig. 12, Plate 8; and Fig. 13, Plate 10, represents a group of crystals taken from the central contraction-cavity of a steel ingot, 47 in. diameter, and weighing 27 tons, at a point about one-fourth of its length below the upper end. This is drawn four times the natural size.

On examining the separate crystals under a microscope, it becomes apparent that they are of the skeleton or discontinuous type, with the larger development of branches in the direction of the octahedral axes. The growth takes place in such a manner that the increase in the direction of one of the principal axes of the crystal is always more rapid than in those of the other two axes, so that each discontinuous crystal presents the appearance of the skeleton of an elongated rectangular octahedron. Besides the growths in the direction of the octahedral axes, which may be called growths of the first order, branches of the second, third, and other orders appear, as the distance from the summit of the group increases; these growths being at first rudimentary, but becoming more and more developed

as they approach the base of the crystal, until they sometimes literally form the skeleton outline of a complete octahedral crystal. An illustrative diagram of such a structure is given in Fig. 14, Plate 10. The largest isolated steel crystals which have been observed, though only rarely, have a length of 5 mm. (0.20 in.); in most cases the length reaches only 3 mm. (0.12 in.) with a diameter of 1 to $1\frac{1}{2}$ mm. (0.04 to 0.06 in.) It is difficult to assign a minimum limit of size, because well-developed crystals have been found, with very accurate contours, so small that they could be clearly seen only when magnified from 100 to 150 times.

The various discontinuous crystals are not usually arranged parallel to each other. Their principal axes intersect at every imaginable angle, as may be seen in Fig. 13. Sometimes however they assume a twin arrangement like that represented in Fig. 15, which is taken from the contraction-cavity of a 5-cwt. steel ingot, and is enlarged 70 times. Fig. 16 represents the outline, enlarged 25 times, of one of the crystals of the group represented in Fig. 13.

Inasmuch as the sides of the contraction-cavities, and of the porous portions surrounding the central contraction-space, are invariably built up of more or less developed discontinuous crystals, it is perfectly justifiable to conclude that the setting of steel does not take place by the uninterrupted addition of smooth layers, but by a continued growth of discontinuous crystals in a radial direction from the cooling surfaces of the mould towards the centre of the ingot; and further that the principal axes of the growths are disposed at right angles to the cooling surfaces, in the manner illustrated in Fig. 17, Plate 11. This is demonstrated in the clearest manner by the radiated structure of the fractures of ingots cast in metal moulds, when the fluid steel has been so hot that no gas bubbles or very few, are found in the outer layers. If the diameter of a cylindrical ingot is small, say from two to three inches, then the rays penetrate to the very centre, as illustrated by Fig. 18; but if the cross section of the ingot is rectangular, Fig. 19, then the fracture shows a rectangle with clearly defined diagonals, formed by the final meeting of the crystals in their growth normally to the surfaces of

the mould. Along these diagonals lie the planes of weakness so well known in ordinary iron castings. It should be noted also that in the contraction-cavities of ordinary iron castings are found discontinuous crystals very similar to those that have just been described; it may consequently be inferred that the setting of cast iron takes place in the same manner as that of steel. Fig. 20 represents a crystal from a contraction-cavity in grey cast iron, enlarged 140 times.

From numerous observations on the structure of the sides of contraction-cavities, it appears that the harder the steel, that is to say the more carbon it contains, the clearer is the development of the discontinuous crystals. In very mild varieties, containing less than 0.2 per cent. of carbon, it is difficult to find well-developed crystals; and when discovered they are of insignificant size. It is highly probable that an intimate relation exists between the faculty for the regular development of discontinuous crystals, and the power of the metal to change rapidly from the perfectly fluid into the solid state, without a more or less protracted passage through the soft dough-like condition, which latter would naturally interfere with the rapid and regular development of the branches of the crystals. This may be seen even in cast iron. The white varieties, or those qualities which are susceptible of being made white by chilling, assume a ray-like structure, indicating a rapid formation of crystals. Grey irons, on the other hand, in which the segregation of graphite hinders the regular process of crystallisation, and which tend to assume the dough-like condition before solidification, take a granular structure; the metal, which at this time tends to form into discontinuous crystals, and to reject the graphite in the neighbourhood of the growths thus being formed, contains very little carbon, although it probably retains all the other substances associated with cast iron. With respect to the confused manner in which the axes of the groups of crystals, in the contraction-cavities and in the central porous column, are disposed, it should be remembered that the cooling in these parts takes place very slowly, through the heated and recently solidified sides of the ingot; and that this state of things is favourable to the formation of a great number of centres of crystallisation, with perfect freedom of direction to the main axes. Besides this, the central portion of the cooling ingot is always in a

state of motion from the shrinking and setting of the metal; and this motion, although very small, is quite competent to turn and disarrange the axes of the crystals.

The chemical composition of the discontinuous crystals, according to the analyses made at the Abouchoff Works, is by no means constant; and is always the same as that of the general mass of the ingot, be it hard or mild steel. Consequently there are no grounds for supposing that a crystallisation is taking place of some definite chemical compound of iron and carbon, although the phenomenon of *liquation*, first noticed and proved by Messrs. Lavroff and Kalakutzkin,* may have given grounds for such a supposition. The discontinuous crystals found in the spots produced by liquation have the same composition as the metal of the spots; but as this metal is always harder than the rest of the ingot, so the crystals are distinguished by more delicate outlines than are characteristic of those which are found outside the spots, and of which the composition is identical with that of the bulk of the ingot.

Turning again to the form of the crystals, it is noticeable that there is no strict regularity in their growth. Sometimes the growth of one side exceeds that of the other; sometimes the branches of the second order grow more rapidly than those of the first, depriving the latter of the material from which they were formed, and then in their turn throw out branches of the third order, and so forth; sometimes the branches meet, unite, and enclose between themselves spaces filled with fluid steel. Fig. 15, Plate 10, represents such spaces, *a, a*, locked in between the growths of the first and second orders. And all this is seen in the examination of one crystal formed by itself. How many of these locked-in spaces must be formed when neighbouring crystals grow side by side and throw out branches in all directions! What takes place in these spaces during the further setting of the steel? The fluid metal continues to act as the source of supply to the growing crystals; but as this involves a shrinkage of the volume of the metal, it follows that each space becomes a contraction-cavity, which may be named, for distinction's sake, a partial or local cavity.

* Journal of the Imperial Artillery, 1866, 1867.

It is evident that the supply of material for the regular development of the crystals cannot go on, if the metal becomes viscid and loses its fluidity; but in the centre of the ingot this loss of fluidity does take place, and is the reason why the structure of the steel becomes more and more porous as the centre of the casting is approached. Near the centre the mass becomes, in fact, little more than a collection of local contraction-cavities. One of these cavities is exhibited in Fig. 21, Plate 12, enlarged 80 times.

On the other hand, the more closely the crystals are packed together, and the quicker their branches grow, the more difficult it becomes for the metal to flow to the crystals in course of formation, notwithstanding that the steel remains very fluid. This state of things exists during the formation of the external layers of an ingot cast in a metallic mould, which rapidly cools the surfaces in contact with it. This is the cause of the formation of the acicular outer layers, and of the comparatively weak lateral adhesion of the component prisms or needles. The local cavities under these circumstances arrange themselves, for the most part, along the planes of contact of the crystals which are forming in directions at right angles to the surface of the ingot. The cross sections of the prisms are generally irregular. This irregularity is caused, in the first place, by the direction of the lateral axes of the neighbouring crystals having no relation whatever to each other; in the second place, by the distance between their principal axes not being equal, so that those very near to each other tend to form twin, triple, and other branches, while the more distant ones develop themselves more independently; and in the third place, as has been already pointed out in describing isolated crystals, by the rapidity of the growth of branches being rarely symmetrical in reference to the principal axes. From these considerations we may imagine the cross section of growing crystals to be similar to that illustrated on an enlarged scale in Fig. 22, Plate 12. At the termination of the growth, the probable appearance of the contiguous crystals is represented in Fig. 23; and indeed this appearance may be actually observed in the fractures of steel ingots of acicular structure. The growth of crystals normally to the sides of the ingot is represented in Fig. 17, Plate 11.

The weakness of cohesion between the prismatic crystals is the chief cause of the formation of external cracks during the cooling of the ingots. The slightest inequality or roughness in the sides of the mould, hindering the free contraction of the cooling external layers, is sufficient to destroy the connection between the prisms, and to cause minute cracks, which are the more numerous the hotter the metal has been, and the greater the consequent contraction. The surfaces of the cracks have a prismatic structure, and the imprints of the discontinuous crystals may be distinctly seen. Fig. 24, Plate 12, represents, full size, the surfaces of a crack which took place, at a bright red heat, during the setting of the external layers of a steel ingot, while the central portion was still fluid. In castings of large diameter, say from 30 in. to 50 in., and of considerable height, say from 7 ft. to 10 ft., and when the steel is very hot and is poured quickly into a metal mould, the rapid expansion of the sides of the mould, acting in a contrary direction to the contracting layers of the steel, has an especially marked influence on the formation of cracks in the skin of the ingots. This inconvenience may in a great measure be obviated by pouring very slowly.

Besides the formation of cracks, the rayed structure of the external layers produces another effect; namely that during the cooling, which takes place more rapidly in the outer than in the inner layers, the former are necessarily thrown into a state of tension, and stretch in consequence; not so much however by the extension of the metal itself as by the destruction of cohesion, and by the separation between the contiguous crystals forming the outer layers, as shown in Fig. 2, Plate 7.

With respect to the granulation which takes place in cooling, inside the outer prismatic surfaces, it can be explained by the fact that this portion of the casting must be in a state of tension while the metal is setting. It has already been explained, in the author's paper on the Manufacture and mode of working of Steel, that, when raised to a high temperature and cooled slowly, steel sets in the form of irregular many-sided grains. If, during the building up of these grains, and while the mass is still red hot, the cohesion of the

metal is enfeebled or destroyed by the action of external forces, *e.g.* tensile or bending stresses, then the chief destruction of cohesion will take place between the surfaces of contact of the grains, and consequently, in the fractured surfaces, detached grains will appear.

This effect may be produced artificially. A piece of steel of the form *a*, Fig. 25, Plate 12, is heated for five or six hours to a bright red or yellow heat: it is then removed from the furnace, and placed between lugs *bb*, projecting from a massive cast-iron plate, so arranged that the steel is securely held from contracting. The piece of steel will be stretched slowly as cooling proceeds; and the cohesion among the grains, which have been formed during the long exposure to a high temperature in the furnace and the subsequent slow and quiet cooling, will be loosened. If the granulation has been very strongly developed, the bar will either tear asunder of itself, or will be very easily broken after it is cold; the fracture exhibiting clearly the granular formation. The same effect may be produced by dropping a steel ring, heated as above described, on to a cast-iron cone. Hard steel is found to granulate more quickly than the milder varieties.

Inasmuch as during the passage of steel through all the ranges of temperature, from its setting point to that of the ordinary temperature of the atmosphere, the strains in the various parts of an ingot are constantly changing from tensile to compressive or *vice versa*, we may expect to meet with such granulations in all portions of a casting; generally however they appear in the outermost and the innermost layers, and especially, in ingots of large diameter, in the places where there is a great difference of temperature between the outer and inner layers. At the commencement of cooling, the outer layers of an ingot are stretched, and the inner ones compressed; at the conclusion of the cooling the reverse action takes place, the outer layers being compressed and the inner ones strongly extended. The tension of the inner layers in ingots of large diameter, such as 40 in., is at times so great that, if left to cool in the open air, the ingots often exhibit internal cracks, especially in their upper and weaker ends.

With respect to the details relating to the granulation of steel, the remarks made in the paper of 1868 are still applicable. Figs. 3

and 26, Plates 7 and 13, represent, at two-thirds the natural size, fractures of a highly granulated ingot. One half of the piece, from which Fig. 26 was taken, is in the museum of the Imperial Russian Technical Society, and one of the grains is illustrated in Fig. 27, magnified seven times. Fig. 28, Plate 12, represents a grain out of another piece, also magnified seven times. It is evident that these grains have only a slight likeness to regular crystals; there is no regularity of form or angle, and the edges are more or less curved and crooked.

We must next consider the methods adopted for overcoming the defects which have been discussed above.

A roundabout way of attaining the object sought is the use of so-called "malleable cast iron." The articles to be produced are cast in white refined iron, and are then exposed for a long time to a high temperature, in some slowly oxidising medium, the effect of which is to decarbonise the iron and so produce a metal more or less analogous to wrought iron and to steel. It cannot be said that this method has solved the problem, because the metal so produced is far from having the qualities which were confidently looked for in the early days of the process. Nevertheless the manufacture of malleable cast iron has received considerable development, especially in substitution for light smithwork, and this is in itself a proof of the difficulty of reaching the desired object by a direct method. It is needless to dwell more particularly on this process, as it will not lead to the solution of the question under consideration.

The methods of overcoming the imperfections in steel castings may be arranged under three heads :—

1. Without altering the system of casting, to limit the ingots to the simplest forms, and to work out the required ultimate shapes by means of hammers, presses, or rolls.

2. To subject the fluid steel, during the process of setting, to heavy pressure; and by that means to prevent the formation of air-bubbles, and to a great extent also of contraction-cavities. The ingots must still be kept to the simplest forms, and reduced to the required shapes by hammering, pressing, or rolling.

3. To use chemical reagents in order to arrest the formation of gases, and thus to obtain castings of the most varied forms and dimensions in ordinary sand or metallic moulds.

By the first method the ingot assumes a structure analogous to that represented in Fig. 1, Plate 7; and the defects which arise vary between the limits indicated on the upper and lower sides of the figure. The head or top portion of the casting, filled with porosities and cavities, has to be cut off and condemned as scrap. This portion amounts to between one-sixth and one-fourth of the weight of the ingot, and bears the same relation to it that the head does to an ordinary iron casting. The remainder of the ingot is sent to be worked up in the forge. With the continued increase in the dimensions of guns, and the adoption of steel for the construction of armour plates, the size of steel ingots has also increased; and, as a matter of necessity, the weight and power of the mechanical appliances used for working them into their ultimate shapes have also been greatly augmented. Accordingly it is found that even 50-ton steam-hammers are no longer powerful enough. At the Paris Exhibition, 1878, the Creusot Works exhibited the full-sized model of an 80-ton hammer then in course of construction, and the model, also full-size, of a 120-ton steel ingot. At the works of Saint-Chamond an 80-ton hammer was also in course of erection, and was expected to be finished within six months. For several years past Krupp has talked of starting a 100-ton steam-hammer; it is not known however in what state this stupendous project stands at the present time.

In preparing ingots for steel forgings, they are so proportioned, with the view of saving as much labour as possible, that the cross section of the casting shall be about double that of the finished article. With this proportion the outer porous layers of the ingot are so far reduced in thickness by forging, that, after removing a comparatively moderate thickness of metal in the lathe or planing machine, a sound finished surface may be confidently looked for. The weight however which is removed by turning or planing, even under these circumstances, amounts to between 10 and 20 per cent. of the finished article; which, added to the head cut off the ingot, represents an important loss of material.

In this system of working it must be borne in mind that the porosity of the inner portions of the ingots, that is the number of local contraction-cavities, is very little reduced in the longitudinal direction; because these cavities do not close, but merely lengthen, in proportion as the surrounding metal is drawn out. In the transverse or radial direction the evil influence of the local cavities is even somewhat augmented; as has been clearly proved by testing the tensile strength of various layers of a thick forged ingot. The following example will illustrate the above statement.

In Fig. 29, Plate 14, is represented, by dotted lines, a cast ingot, the diameter of which is D' . The full lines represent the same ingot, after having been forged under a 50-ton hammer and reduced in diameter to D . After forging, a central hole, of diameter d , was bored out, and at a seven strips were cut out parallel to the axis of the ingot. Specimens prepared from these strips were tested for tensile strength, and gave the following results for various values of D' , D , and d :—

Diameter in inches.			Position of Specimen as numbered on the ingot.	Limit of Elasticity.	Ultimate Strength.	Ultimate Elongation.
D'	D	d		Lbs. per sq. in.	Lbs. per sq. in.	Per cent.
47.5	36.5	11	1	26468	77910	16.0
			7	34251	91140	17.0
42.5	32.5	9	2	29106	76440	18.0
			6	36750	94080	16.0
36.5	26.5	8	2	26460	85701	13.7
			5	34986	96138	14.8
36.5	26.5	8	1	27342	66400	16.0
			7	42777	96800	15.0

Inasmuch as the ingots out of which the specimens were taken had all been forged, the question may be asked, whether the superior strength of the outer layers of the material cannot be explained by

the circumstance that they came more immediately under the influence of the hammer. In reply it may be stated that the ingots, after having been forged, were annealed with more or less rapid cooling, and that during this operation the various layers were not in an identical condition; but the samples cut out, before being tested, were annealed again, under precisely similar circumstances for each pair, and with slow cooling after heating. By this annealing the influence of unequal forging was materially reduced, and therefore the difference of strength must, in a great measure, be referred to local cavities. It is much to be regretted that no opportunity presented itself of making similar experiments on unforged ingots of like dimensions.

To demonstrate the existence of local cavities in forged ingots, it is only necessary to examine Figs. 30 and 31, Plate 14, which show the shape and distribution of local cavities, in forged ingots of similar size and quality with those from which the foregoing specimen strips were taken. The drawings are made half the natural size, from polished strips cut out of forged ingots in the radial direction, as indicated at *b* in Fig. 29. The figures show that forging has caused the cavities to elongate in the direction of the axis of the ingot, so as to give them an elliptical shape; and that the number of cavities increases as the centre is approached.

We have next to examine the second method, or that of compression.

The investigation already made into the phenomena accompanying the setting of steel makes it clear that, if it were possible to cast steel under an atmospheric pressure sufficiently great to keep the occluded gases in solution, then the resulting ingot would be perfectly free from gas bubbles. With this view Galy-Cazalat in 1866 proposed to cast steel under the pressure of gunpowder gases, and in France it has been suggested to use steam under a pressure of from 6 to 10 atmospheres. This method is no doubt sound in principle; but it is of little practical value on account of the many inconveniences attending its application, where the character of the products required is so miscellaneous.

Very much simpler is the process of applying pressure through a solid piston, acting on the surface of the freshly cast ingot, and thus producing the so-called "fluid-compressed steel." This system has received some important practical applications, and deserves therefore to be particularly dwelt upon.

The steel is poured into the mould in the ordinary manner, and immediately afterwards its upper surface is pressed by a solid piston, actuated by hydraulic power. The gases which had begun to collect in bubbles on the sides of the mould become reabsorbed under the influence of the pressure, and the cavities are filled with fluid steel, which thus takes the place of the bands of air-bubbles found in other cases. But in order that this absorption of gases out of the bubbles formed along the sides of the mould may take place, it is indispensable that the metal surrounding these cavities should remain fluid, at any rate on one side; in other words, that the pressure should be applied before a thick layer, locking the bubbles in on every side, has had time to form along the surfaces of the mould. With the view of furthering this object, the mould is lined with a refractory and badly-conducting lining. The pressure is usually maintained for a length of time sufficient to enable a thick crust to be formed over the entire surface of the ingot; by this means the escape of the gases is prevented, and these, as has been already pointed out, will by their tension prevent the further evolution of gas in the body of the casting. If this was the only duty the hydraulic press had to perform, one of moderate power would suffice, because it does not require much pressure to stop the evolution of gas. But if it is also intended to do away with the funnel-shaped contraction-cavities, then the press must be much more powerful, in order that the piston may follow the shrinkage of the metal up to the moment when setting takes place in the central portion of the ingot. This is the aim that Sir Joseph Whitworth proposed to himself in constructing his large press, the dimensions of which are truly colossal; for the diameter of the hydraulic cylinder is 50 in., and the water-pressure as high as 5 tons per sq. in., so that the full pressure which may be exerted amounts to 10,000 tons.

It is difficult to say to what degree this press attains the object

of annihilating the cavities in large ingots; for the specimen exhibited by Sir Joseph Whitworth in Paris had a diameter of only 12 to 13 in. and a length of 3 to $3\frac{1}{2}$ ft. It was cut in halves longitudinally, and the cut faces were polished; it was certainly impossible to detect, through the glass case at any rate, the presence of any contraction-cavities, the ingot appearing to be perfectly solid. The method of pressure however, notwithstanding its many apparent advantages, has not, up to the present time, been applied to castings of complex form. Besides this it is well known that Sir Joseph Whitworth does not content himself with fluid pressure only, even for articles of the simplest shape, *e.g.* the rings of heavy guns, shot, shell, tubes of guns, and the like; but subjects them also to forging, under a hammer or by pressure. Consequently fluid pressure alone does not solve the problem of bringing steel direct into the various shapes required. It adds indeed to the economy of manufacture and of metal, by doing away with the "head," which has to be sacrificed in the ordinary process, and by reducing to a minimum the allowance for boring, turning, or planing after forging. But even these advantages are obtained at great cost, in the shape of the very large capital necessary for the construction of the press and its accessories, besides the working expenses, which are considerable; and this cost, charged on the comparatively small output of a press, is far from being recouped by the saving realised. This is probably the reason why, in western Europe, the adoption of the Whitworth system has been confined to the inventor's own works.

The last method of vanquishing the difficulties surrounding the steel founder is distinguished from the others in that it completely solves the question, and is based on scientific research.

A partial success, in the harder kinds of steel, was obtained more than twenty years ago, by Mayer, at the Bochum works; and his method was adopted by several German, Austrian, and English factories. As examples of this process, the Bochum bells, of which some 3,000 have been made up to this time, are especially famous; and various other castings, such as wagon and locomotive wheels,

crossings, sundry ironwork connected with railways, screw propellers, cylinders for steam engines and hydraulic presses, toothed wheels, &c., have been turned out with success.

All the above articles are cast in sand moulds, out of steel comparatively hard and rich in carbon, melted in crucibles; each charge having added to it a considerable quantity of siliceous pig-iron, which imparts to the metal from 0·3 to 0·4 per cent. of silicon. As soon as this method, which was at first kept secret by the works where it was adopted, became more generally known, it fell under the scrutiny of scientific metallurgists, and it was soon found that the soundness of the castings was due to the presence of silicon in the steel, and that this substance acted in a twofold manner. On the one hand it materially diminished the solubility of gases in steel during the melting of the metal, and on the other it impeded the formation of carbonic oxide, a formation due to the reaction of the oxygen, which is dissolved in the steel during melting, on the oxide of iron and the carbon.

Inasmuch as melting in closed crucibles protects the metal in a great measure from the oxidising effects of the atmosphere, and at the same time the greater proportion of carbon in hard steel makes the latter less liable to dissolve the oxides of iron, the production of sound castings from the crucible is less difficult than when soft Bessemer or Siemens-Martin steels are used. At the present time however, judging from their display at the Paris Exhibition, the Terre-Noire works have overcome the last difficulties surrounding the art of producing perfect steel castings.

In order to obtain mild steel from the Bessemer converter or the Siemens-Martin furnace, it is well known that it is necessary, at the close of the operation, to add considerable quantities of manganese, in order to reduce the oxide of iron dissolved in the fluid metal. Spiegeleisen is employed for this purpose, on account of the large quantity of manganese it contains; and, for very mild qualities of steel, the so-called "ferro-manganese" is used. This has a similar composition to spiegeleisen, that is, iron, carbon, and manganese; but the proportion of the latter is so large that the fracture of the metal no longer presents the large mirror-like facets which characterise spiegeleisen.

The honour of introducing the use of mixtures of iron bearing a very high proportion of manganese, reaching even to 80 and 85 per cent., belongs to the engineers of the Terre-Noire works, under the management of M. Euverte; and to them also must be ascribed the credit of adding a large quantity of silicon, and thus achieving the important end of obtaining sound castings out of mild Siemens-Martin or Bessemer steel. It is well known that in the Bessemer converter, as well as in the furnaces of Martin and Pernot, the silicon, which is contained in the fluid metal at the beginning of the process, nearly all becomes oxidised, and disappears in the slag; the exception being when the Bessemer process is carried on at a very high temperature, and with pig-iron containing a large percentage of silicon. It happens therefore that at the end of the process the metal is generally free from silicon; and as neither spiegeleisen nor ferro-manganese contain much silicon, it results that the steel, after the addition of either of those two substances, is very little richer in silicon than before. This is the reason why both Bessemer and Siemens-Martin steel hold large quantities of gases and oxides in solution, and why castings made from them are generally permeated with gas-bubbles. The ferro-manganese-silicon meltings, now produced at Terre-Noire, furnish the means of introducing into the final product of the Bessemer or Siemens-Martin process such quantities of silicon as are indispensable for the perfect decomposition of the carbonic oxide dissolved in the metal; and for the formation of a double silicate of iron and manganese, during the reduction of the iron oxides which are also dissolved in the steel. This double silicate, being very buoyant and fluid, rises with comparative freedom to the surface; and in this manner very effectually clears the metallic bath of the finely-divided slags, which exercise a pernicious influence on the mechanical properties of the steel produced.

According to M. Pourcel, the new mixture is added at the end of the process, before casting, and in such quantities that the cast metal should contain 0.2 to 0.3 per cent. of silicon. In order to neutralise the pernicious influence of silica on the stability of the union between the iron and the carbon, it is necessary to introduce

such a quantity of manganese that the proportion between the silicon and the manganese should be as 2 to 3.*

Steel produced under these conditions pours into the moulds quickly without boiling up, and produces castings free from bubbles. To reduce contraction-cavities, heads are used as in iron castings. The splendid collection of cast-steel articles, shown by the Terre-Noire works, proves that the problem of obtaining the most complex forms of steel by direct casting into moulds is now very near its complete solution.

Even if it cannot be said that the difficulties surrounding the production of perfectly sound castings out of *pure steel* have been completely vanquished, yet it is fit that full recognition be made of the services rendered by the Terre-Noire works in preparing, by rational and scientific investigation, a way to the desired end. It may now be said that the veil has at last been lifted, which concealed so long from the eyes of numerous investigators the cause of the porosity of steel castings. It remains still to discover how to reduce the addition of silica to a minimum, in order to avoid, as much as possible, the use of manganese, which is necessary to neutralise the action of silica in withdrawing the carbon from its union with the iron. No less important are the investigations of Pourcel on the fluidity and subsidence of the silicates produced by the addition of ferro-manganese, at the end of the conversion, in the manufacture of Siemens-Martin and Bessemer steel.

Among the castings exhibited by the Terre-Noire factory, the following claim special notice.

(1.) Two shots of 0·32 m. ($12\frac{3}{4}$ in.) diam. and 0·786 m. ($30\frac{1}{4}$ in.)

* It is assumed that silicon possesses the property of separating carbon, in the form of graphite, from its combination with iron. The experiments of Caron have shown that if steel, rich in carbon and also containing much silicon, is heated frequently and for a long time, without being forged, or is repeatedly annealed, it deteriorates greatly, because nearly the whole of the carbon becomes separated in the form of graphite. Manganese, by combining with the silicon, prevents this action taking place; and hence, in the best Sheffield steel, the presence of manganese is considered an indication of superior quality, although it would be utterly useless but for the occurrence of silicon.

length, which had passed through iron armour 0·30 m. ($11\frac{3}{4}$ in.) thick, backed by 1 m. (3 ft. $3\frac{3}{8}$ in.) of timber. The shots struck the target at an angle of 20° and remained uninjured, with the exception of a slight deformation of the heads, by which the projectiles were shortened by from 14 to 19 mm. (0·55 to 0·75 in.), the diameters were increased by 0·5 mm. (0·02 in.), and the points were deflected 17·5 to 27 mm. (0·68 to 1·05 in.) from the axis.

(2.) The inner tube for a 14-centimetre ($5\frac{1}{2}$ in.) naval gun. This tube had been tested by a committee on naval artillery experiments at Ruelle. One hundred rounds had been fired, commencing with charges of 4·2 kg. (9·3 lb.) of powder and 18·65 kg. (41·1 lb.) of shot, and ending with 4·9 kg. (10·8 lb.) of powder and 21 kg. (46·3 lb.) of shot. The deformation proved to be somewhat less than with forged steel tubes tested under like conditions.

(3.) An experimental tube that had stood the powder test at Bourges.

(4.) A rough turned ingot for a 24-centimetre ($9\frac{1}{2}$ in.) gun; weight $11\frac{1}{2}$ tons.

(5.) Inner tubes for guns of 24- and 32-centimetre ($9\frac{1}{2}$ in. and $12\frac{3}{4}$ in.) calibre, and a trunnion ring for a 42-centimetre ($16\frac{1}{2}$ in.) gun, weighing $6\frac{1}{2}$ tons; a crank for a steam engine of 400 H.P.; a locomotive crank-axle, and so forth.

The finish of all these articles would compare favourably with that of the best iron castings. In the thicker ingots however, and especially in the central parts, the fractures showed, scattered here and there, those local contraction-cavities which have already been minutely described.

On examining the region of bubbles entangled in the central parts of steel ingots, it will be seen that in most cases the lower half of a bubble has a more or less smooth hemispherical form, while the sides, and especially the upper portions, are covered with arborescent growths of the most varied forms, as shown magnified in Fig. 32, Plate 14. On carefully comparing these arborescences with the discontinuous crystals of the contraction-cavities, it will be noticed that a similarity exists between them, and that the arborescences are in fact formed from the

crystals encountered by the bubble in its upward movement, at a time when the steel has so far set, that is, has become so far filled with discontinuous crystals, that the bubble cannot freely rise to the surface. As the bubble floats upwards, motion of the surrounding fluid takes place; the floating crystals are moved aside and turned over, and as they are at the same temperature as the surrounding fluid, they are very tender, and apt, on the least provocation, to dissolve again. Consequently, during the passage of a bubble, the crystals are partly dissolved and partly transformed; they interlock with each other and form arborescences of the most complicated shapes, so much so that it is frequently impossible to find any likeness to the discontinuous crystals from which they were originally produced. This may be seen in Figs. 33 and 34, Plate 14, the latter representing one of the arborescences detached and magnified 80 times.

From what has been said above it is evident that in order to destroy the discontinuous crystals which are constantly forming, in other words to effect their complete solution in the surrounding fluid mass, it is sufficient to give to that mass a comparatively slow movement, seeing that the motion of the gas bubbles alone is almost enough to accomplish the same object. This circumstance leads to the conclusion that it is possible to prevent the acicular formation of the outer layers of ingots cast in iron moulds, as well as to obliterate the local cavities or porosities of the central portions.

In fact, if, during the pouring of an ingot, the mould were caused to rotate with considerable velocity, then the discontinuous crystals tending to form at right angles to the sides would not be in a condition to develop so rapidly as if the mould were at rest; and the steel would set in smooth layers of amorphous structure. If the rotation is continued till the central core of the ingot has set, then the whole mass will present a uniform structure, and all causes for the formation of local cavities will cease. The casting will be perfectly sound throughout, and will not require to be consolidated either by hammering or by pressure. It will be sufficient to anneal the ingot, in order to destroy the coarsely crystalline formation which the metal receives after it has set, during the slow subsequent

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cooling. Inasmuch as in the beginning of the pouring, in consequence of the powerful cooling action of the mould, the crystals grow very rapidly, it is necessary that the rotation of the mould should be rapid; but as the friction between the sides of the mould and the fluid steel will cause the latter also to revolve, it will be necessary from time to time to alter the direction of rotation, in other words to cause the revolution to take place in alternate directions at tolerably short intervals.

For cylindrical ingots in which an axial bore is afterwards to be made, such, for example, as those prepared for the manufacture of breech-loading guns, it would be more convenient to cause the mould to revolve on a horizontal axis, and with this object to turn it on its side, as soon as the crust over the upper open end had formed. The contraction-cavity would then be distributed evenly along the whole length of the axis, instead of forming a funnel at one end; and there would be no need to add any considerable head of metal. For shell, when unforged, and cast at once to the finished form, as at Terre-Noire, the rotation would answer best on an inclined axis, since it would then tend to produce a long funnel-shaped cavity, very nearly of the shape required. It is impossible not to admit that the constant mixture of the metal during rotation will tend to create uniformity of structure and prevent liquation.

The above description brings to mind the so-called "centrifugal system" of casting, but the similarity is superficial only. Up to the present time the idea of centrifugal casting implies the development and use of centrifugal force in order to consolidate the metal in a radial direction; as for example in the tread of a cast-iron wagon wheel. If it is really a fact that, with the centrifugal method of casting, the iron becomes more sound and compact, then this effect must not be ascribed to centrifugal force, but only to the circumstance that the motion produced in the liquid metal hinders the formation of discontinuous crystals. It is highly probable that the use of this process would very greatly improve the qualities of chilled cast-iron rolls, of cast-iron ordnance and projectiles, and of some kinds of brass castings.

There still remains one question to discuss—a question which has already been considered in the author's paper of ten years ago, on the Manufacture of Steel—namely whether forging is necessary to steel, even when cast perfectly sound, without bubbles or local contraction-cavities. To answer this question it would be sufficient to refer to the experiments made in 1869 by a Committee of the Technical Society (see their Proceedings, 1870, second issue); but several new facts are available, and these are embodied in Tables I. and II. appended.

A comparison of the figures in these two Tables shows the uselessness of any kind of pressure or forging to improve the mechanical properties of steel. The whole question lies in the skill of the founder. The low mechanical properties which distinguish unannealed cast steel, whether compressed or not, from annealed or forged steel, can be explained by its coarsely crystalline structure, by the presence of local cavities, and especially by granulation. This latter defect is only partially removed by annealing, which may be explained by the circumstances that the surfaces of contact of the grains are separated by varying distances; and that these distances always exceed the limits within which cohesion acts at ordinary temperatures, but not, in general, its limits at a bright red heat. If these latter limits are not exceeded, then, when the steel is heated for annealing purposes, the grains stick together. It happens most frequently that only some of the grains adhere to each other, those namely which are not separated beyond the limits of cohesion at a high temperature, while the remainder do not unite. In this manner, in most cases, granulation is only lessened, and not entirely destroyed, by annealing.

Granulation is further developed by the tension produced during the cooling of the castings, and while they are still at a red heat. The outer layers are brought into a state of tension at the commencement of cooling, and the inner ones towards the end. In this respect Sir Joseph Whitworth's method of casting with an internal core is objectionable; the core hinders the free contraction of the annular-shaped casting, causes the metal to stretch, and so favours the development of granulation. This is the reason why

strongly compressed steel in the form of annular ingots has comparatively low tensile strength, even after having been annealed. It is well known that Sir Joseph Whitworth forges or otherwise works his steel after pressing; and a comparison of Tables I. and II. demonstrates that it is only after forging that annular-shaped compressed steel can compare in mechanical properties with the cast and annealed steel of the Terre-Noire works.

It may here be noted that Sir Joseph Whitworth's results show remarkably great elongation in his steel before rupture; but it should be borne in mind that his samples were only 2 inches long, while all other makers make use of specimens 8 inches long, which only give about half the proportionate extension under tensile tests.

The conclusion to be drawn from what has now been discussed is the following.

The problem of preparing sound castings, direct from the mould, may be considered solved as far as the absence of gas-bubbles is concerned; and this is the point of cardinal importance, whether the result be obtained by the high temperature at which the metal is poured, by the use of silicon, or by subjecting the casting to moderate pressure, say six to ten atmospheres. To give the steel so obtained its best internal structure, and the necessary mechanical properties, it is sufficient to anneal it, with a more or less rapid cooling or tempering.

Special attention in casting has to be devoted to the suppression of contraction-cavities and granulations, whether grain-like or prismatic in form. These can be prevented, as has been shown, by proper methods; among the best of which is that of keeping up motion in the melted steel which is in contact with the solidified layers. Granulations will be avoided by the use of sand, or other non-conducting, moulds, by letting the castings cool slowly, and by removing all obstacles to the free contraction of all the parts of the casting. The same precautions will prevent the formation of cracks.

For the most simple forms these requirements are most readily met—and that without necessitating a high temperature in the metal,

which is specially important with respect to granulation—by the use of substantial cast-iron moulds, thickly perforated with holes, and protected by a fire-resisting lining of moderate thickness.

The compression of fluid steel by means of a solid piston appears to be applicable only to the simplest forms, and to have no real future before it. The hammer and the rolls would still be necessary for the production of such ordinary shapes as cannot by casting be produced sound and with a smooth skin.

TABLE I.

EXPERIMENTS ON THE TENSILE STRENGTH OF STEEL
AT THE TERRE-NOIRE WORKS.

Diameter of Specimens, 14 mm. (0·55 in.)

Length of Specimens, 100 mm. (3·93 in.)

Nature of Specimens.	No. of Specimen.	Percentage of Carbon.	Elastic Limit.	Ultimate Strength.	Final Elongation.
		Per cent.	Tons per sq. in.	Tons per sq. in.	Per cent.
FORGED STEEL. (Containing about $\frac{1}{4}$ per cent. of manganese and a trace of silicon.)	1	0·150	13·70	22·24	34·0
	2	0·490	16·32	30·40	24·0
	3	0·709	19·69	42·36	15·0
	4	0·875	21·31	46·16	9·5
The same after annealing in oil. (Composition as above.)	5	0·150	20·43	28·16	28·6
	6	0·490	27·79	43·92	12·0
	7	0·709	42·86	66·72	4·0
	8	0·875	56·38	66·14	1·0
CAST STEEL NOT FORGED. (Containing about $\frac{5}{8}$ per cent. of manganese and $\frac{1}{4}$ per cent. of silicon.)	9	0·287	13·08	27·85	8·8
	10	0·459	16·51	26·98	5·0
	11	0·750	19·00	40·00	3·5
	12	0·875	24·42	40·18	1·5
The same after annealing in oil and tempering. (Composition as above.)	13	0·287	19·69	32·27	24·6
	14	0·459	20·87	34·58	19·2
	15	0·750	22·30	46·23	14·3
	16	0·875	28·66	51·46	3·5

TABLE II.

EXPERIMENTS ON THE TENSILE STRENGTH OF STEEL
AT THE ABOUCHOFF WORKS.

Diameter of Specimens, 12.5 mm. (0.49 in.)
Length from 150 mm. to 250 mm. (5.91 to 9.84 in.)

Nature of Specimens.	Elastic Limit. Tons per sq. in.	Ultimate Strength. Tons per sq. in.	Final Extension. Per cent.	Remarks; and Percentages of Carbon, Silicon, and Manganese.
From an 8-in. Bessemer steel shot, No. 2046 Abouchoff Works; not forged nor annealed . . .	16.38	39.37	4.0	Mean of two analyses. { C = 0.70; Si = 0.07; Mn = 0.54.
Ditto, annealed . . .	24.93	46.59	8.0	
Forged Bessemer gun steel, No. 1095	17.71	39.37	16.5	{ C = 0.43; Si = 0.04; Mn = 0.30.
Ditto, second sample	18.43	40.02	15.5	
Forged and annealed Bessemer steel, from rings of 9 in. mortar (result of many samples) . . .	16.40 to 18.37	42.65 to 48.55	20.0 to 14.0	{ C = 0.35; Si = 0.01; Mn = 0.12; to C = 0.45; Si = 0.10; Mn = 0.30.
Forged 11-in. shot of Krupp's manufacture . . .	..	45.27	10.0	{ C = 0.68; Si = 0.23; Mn = 0.29.
Unforged annealed 9-in. shot of Terre-Noire make . . .	24.93 to 26.24	46.59 to 53.15	3.4 to 5.6	{ C = 0.57; Si = 0.24; Mn = 0.29.
Unforged annealed 9-in. shot, Isnoskoff's make . . .	36.74	36.74	0.4	{ C = 0.72; Si = 0.22; Mn = 0.61.
Fluid compressed steel, pressure about 2100 atm.; 1. Without further working . . .	18.59	30.61	2.4	Crucible steel containing about C = 0.54. Mean of 6 specimens. " " 4 " " " 2 " " " 2 "
2. Annealed . . .	20.83	34.61	6.7	
3. Forged and annealed . . .	21.00	42.00	16.0	
Fluid compressed steel, pressure of about 1200 atm.; forged and annealed . . .	17.39	32.15	18.1	

Fig. 1. *Longitudinal Section of Cylindrical Ingot.*

Fig. 2. *Acicular structure. Full-size.*

Fig. 3. *Granular structure. Two-thirds full size.*

Modes of formation of Bubbles.

Fig. 4.

Fig. 5.

Fig. 6.

Fig. 7. Scale $\frac{1}{16}$ th

Fig. 12. Central Cavity in top of Ingot. Full size.

Fig. 8.

CAST- STEEL INGOTS.

Plate 9.

3 ton Ingot of Compressed Steel.

Fig. 9.

Scale $\frac{1}{16}$ th.

Fig. 10.

Enlargement of a. b. c.

Scale $\frac{1}{16}$ th.

Fig. 11. Section at b.c. Scale $\frac{1}{2}$

Fig. 13.
*Crystals from cavity
in top of Ingot.*

Scale 4 to 1.

Fig. 14.
Skeleton Octahedral Crystal.

Scale about 300 to 1.

Fig. 15. *Trin Crystals
from Steel Ingot.*
Scale 70 to 1.

Fig. 16. *Outline of Crystal.*
Scale 25 to 1.

CAST-STEEL INGOTS.

Plate II.

Direction of growth of Crystals.

Fig. 17.

Cooling surface

Fig. 18.

Fig. 19.

Fig. 20. *Crystal from
Grey Cast Iron.
Scale 140 to 1.*

Fig. 21. *Contraction Cavity
in centre of Steel Ingot.
Scale 80 to 1.*

Fig. 22.

Fig. 23.

Fig. 24. *Full size.*

Fig. 25.

Fig. 28. *Scale 7 to 1.*

Fig. 26. Fracture of Granulated Ingot.

Two-thirds full size.

Fig. 27. Grain from Fig. 26.

Scale 7 to 1.

Fig. 29.

Fig. 34.

Scale 80 to 1.

Fig. 30.

Strips cut at b, Fig. 29. Half full size.

Fig. 31.

Bore of Gun

Magnified Sections of Bubbles.

Fig. 32.

Fig. 33.