THE METALLURGY OF STEEL.

VOLUME II.

THE MECHANICAL TREATMENT OF STEEL.

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CHAPTER XX.

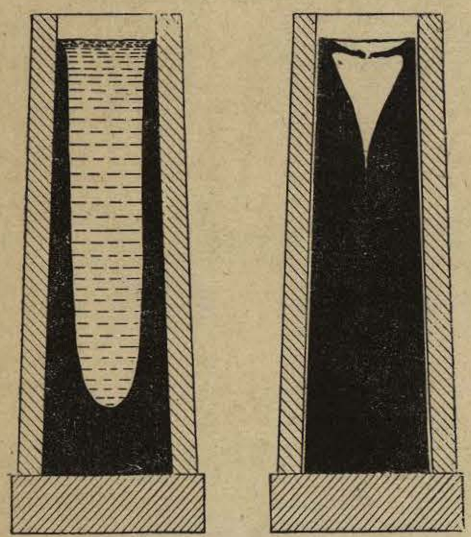
GENERAL PRINCIPLES.

Need for Mechanical Working.—When the chemical reactions involved in the manufacture of steel on a commercial scale are completed, except in the case of shear steel, the use of which is declining, the metal is in a fluid state; even puddled and cemented steels are remelted to rid them of slag and ensure uniformity of composition, so that practically all steels are obtained in a molten condition, and must be poured into ingot moulds to cool, before they can be worked into the forms required for use. The squeezing exerted on the exterior during the process of working by pressing the particles into more intimate contact and by breaking up the weak, coarsely-crystalline structure much improves the quality, and has a most important effect on the metal apart from its mere reduction to form or size. Even if it were possible to run the fluid steel directly into moulds having the form of the finished articles (which for various reasons it is not generally practicable to do), material so shaped would, like steel castings, be inferior to that which had been worked by the rolls, the hammer, or the press.

Steel, cast to form, does not possess the same qualities as that worked into shape, because the metal, while passing from the fluid to the solid condition, contracts to the extent of about practically $\frac{1}{50}$ of its linear dimensions, and if the contraction were not resisted by other forces it would exceed this amount. We may, without sensible error, regard contraction as directly proportional to the fall in temperature, and if cooling could proceed uniformly throughout the entire mass, every particle would contract at the same rate, and the fluid steel which had been poured into an ingot mould 25 inches square, would be found changed into a solid mass something less than $24\frac{1}{2}$ inches square, the material being of uniform consistency and density throughout, and in a perfect physical state.

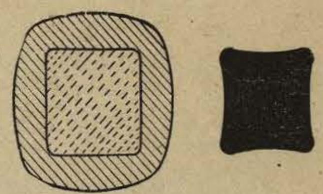
Such conditions cannot possibly occur in practice, because that portion of the fluid steel next to the cold mould is rapidly cooled by it, and a thin outer shell of solidified metal forms instantly; the heat contained in the fluid portion then escapes through this outer shell in lines at right angles to the surface, the fluid interior freezing up to the outer shell, layer by layer, as the heat is dissipated.

The effect this has on the metal can be best realised by considering what would occur if the molten steel could be poured into a closed spherical mould of equal thickness all over, so that the heat would escape equally in all directions, and if the mould were turned continually into different positions during the process of cooling, so as to counteract the force of gravity, which would naturally draw the fluid to the bottom of the mould, leaving a void space at the top. If in such a mould an infinitely thin outer shell of the fluid metal fell at once to atmospheric temperature, taking the exact form and size of the mould, and the rest froze up to this shell at the same temperature, continuously, until the whole was set, we should find the metal



A. B.

Fig. 290.—Section of Ingot showing Piping.



A. B.

Fig. 291.—Cross-section of Ingot and Mould.

in the form of a hollow sphere 25 inches diameter outside, having a spherical cavity exactly in the centre not less than 9¾ inches in diameter, this hollow being the 6 per cent. difference in volume of steel when fluid, and when cooled to the temperature of the air. If, on the other hand, the mould were formed of a non-conducting material, and the fluid contents could be in any way cooled from the middle, a minute particle in the very centre of the mass falling to atmospheric temperature, and the rest depositing around this central nucleus in infinitely thin successive layers, we should have a solid sphere something less than 24½ inches in diameter.

The ingot mould in common use consists of a tall square iron box, without top or bottom. Immediately the molten steel is poured into it, thin skins of solidified metal form on the cold sides of the mould, A, fig. 290, and then a thinner skin on the surface of the metal, which is exposed to the air. As the fluid metal contracts, this upper crust loses its support, and sinks into the form of a saucer, while the skin on the sides keeps thickening by the addition of successive solidified layers. All this time the level of the fluid in the centre is falling steadily, so that the walls which are thin at the top where first formed, increase in thickness downwards as more time is allowed them in which to collect material from the fluid core, until there is at last no fluid left. The result is that a hole having the form of an inverted cone, with a thin skin above it, is formed at the upper end of the ingot, as shown in B, fig. 290, technically known as a "pipe." Under certain conditions, such, for instance, as the use of an immoderate amount of Silicon, or more especially of Aluminium, this pipe may extend downwards throughout the greater part of the length of the ingot. By attention to the chemical composition of the metal, piping may be considerably reduced, while by certain mechanical methods of treatment to be described in Chapters xxxix. and xli., it can be largely avoided.

In any case the feeding of the lower central portion of the ingot cannot continue after the metal has attained to a plastic condition, but as the contraction still continues, the central portions which cool last find themselves contained in a rigid shell, which, when they have fallen to atmospheric temperature, is far too large for them, so that the particles are stretched out in all directions to fill it. The first portion of this contraction occurs when the metallic crystals are just forming in the sluggish fluid, in which state the steel somewhat resembles moist brown sugar, the crystals of which are held together by the treacle it contains. At this critical point, when the action of gravity is insufficient to keep the semi-fluid particles in contact, and metallic cohesion has scarcely begun, steel has practically no tensile strength, and is easily ruptured by its own contraction, or that of the parts around it, and as the material will not weld, a flaw once formed can never be got rid of.

To relieve these internal stresses ingots, where possible, are cast square or rectangular in cross-section, so that the flat sides which have set, but are still comparatively soft, may be pulled inwards by the contracting centre, the change of form affording the requisite relief (see B, fig. 291, where this change of form is somewhat exaggerated to make the change more readily visible). If the corners were left sharp they would cool much sooner than the rest of the skin, setting up further strains, and to avoid this they are well rounded, and the walls of the mould made thinner at these parts (see fig. 291), which serves to further equalise the temperature of both ingot and mould, and so prolong the life of the latter. When ingots are made circular in cross section, the temperature of the skin and mould is the same all round, but no relief by change of shape being afforded when the centre contracts, such ingots are more liable to internal flaws than rectangular ones.

There is, however, no escape from the fact that the centre of any ingot must set later and remain hot longer than the outside, with the result that the centre is always more or less in a state of tension; and though no actual rupture may occur, pieces cut from the centre have a considerably lower tensile strength, accompanied by very much less elongation before fracture, than pieces cut from the outside of an ingot. If an unworked ingot is cut in two longitudinally and the surface polished, no difference in the closeness of grain may be visible, but if the surface is etched with acid the looseness of texture, extending for a considerable distance below the pipe, may generally be seen by the naked eye.

For this reason the exterior of an ingot is not improved by working so much as is the interior, which, when properly worked, though never quite so strong, may be brought to nearly the same physical condition as the surface. Still, for practical purposes, a well-worked bar, made from a sound ingot, may be regarded as homogeneous, and of uniform quality throughout.

Fortunately, for most purposes the soundness of the outer surface is of more importance than that of the smaller central core, but in the case of tool steel, which has to be drawn out to form a chisel or drill, the centre is the more important portion, because it forms the cutting point. Accordingly tool steel is carefully poured from a crucible in the smallest practicable stream into the centre of a mould of small cross-section, about 3 inches square, standing at a slight angle from the perpendicular, in order that the stream of fluid metal may pass down the exact centre of the mould. These small ingots cool rapidly, while the slow and steady supply of fluid metal in the centre leaves as small a portion of the ingot as possible at any time in the plastic state. The weakness of structure due to the change from the fluid to the solid state is not peculiar to steel; all cast metals are, from the same cause, subject to the same defect, and, therefore, those which are malleable after casting are much improved by working. As the looseness of the texture is due to the passage from a fluid to a solid state, when once the cast metal has been properly worked, no serious mechanical injury is done by reheating, unless the temperature approaches that of fusion; nevertheless, it is always advisable, if possible, to put some work on steel after every heat.

The object, therefore, of working steel, is to remove the internal stresses and looseness of texture inherent in any metal produced by fusion and afterwards cast, and of all the known methods of shaping the cast material, by far the most important, the most efficient, and the most extensively employed, is the process of rolling the heated metal between rolls, as devised by Cort in 1783 for finishing puddled iron.

Rolling—Introductory.—The method as introduced by Cort was subsequently used for finishing the steel made by Bessemer's process from its introduction in 1855, with practically no modification, if we except the introduction of the three-high mill in 1857, until Mr. Ramsbottom put down the first reversing mill at Crewe in 1866. From that date the rolling mill has passed through a surprisingly rapid process of development in size and power, and aided by the numerous subsidiary appliances for handling the material mechanically during the process of rolling, the use of which began in a crude form about the same time, now differs so materially from its original form that a modern mill will produce ten or twenty times as much, and a rod mill fifty to a hundred times as much in a given time, as one of the same size could have done forty or fifty years ago.

These alterations have arisen naturally from the essential difference in the methods by which iron and steel respectively are produced.

Iron-making.—Iron is made in a puddling furnace requiring severe physical exertion on the part of the workman, the success of the process depending largely on his physical powers, which experience proves are not sufficient to enable him to deal efficiently with more than about 5 cwts. of metal at a time. When the puddled iron is ready for removal it is in a plastic state, and while in the furnace is formed by manual power into five balls of about 1 cwt. each, which is as much as a man can properly handle. These balls are hammered to expel the slag mixed with the particles of iron, as a sponge is squeezed to expel water. Several balls may be laid on each other and all hammered together into one mass, but when more than 4 or 5 cwts. are dealt with at one time it is not easy to drive the cinder out of the centre of the mass, and rarely more than two at the most are worked together. The hammered balls are rolled while still hot into a "puddled bar." The bar is cut up when cold into short lengths, which are laid one on the other to form "piles," which are raised to a welding heat and rolled down into the section required.

The piles must enter the rolls at a welding heat, at which iron is so soft that only short pieces can be lifted by one end, and they must be finished while still at a high heat, or the iron will be spoiled. In short, the process of iron-making consists in continuously building up small pieces into larger by sticking them together at a welding heat, all the operations being most conveniently conducted with small quantities and on a small scale. Hence iron works are laid out so that the comparatively small puddling furnaces are grouped as closely as may be round the "shingling hammer" and "forge train," and the reheating furnaces as closely as may be round the finishing mill, to avoid the risk of the small pieces cooling in transit, and the best results are obtained when light bars are rolled off in short lengths.

Steel-making.—In steel-making we find these conditions all reversed. Steel cannot be produced economically in small quantities, and has to be made in Bessemer vessels dealing with from 5 to 20 tons, or in open hearth furnaces melting from 10 to 150 tons at a time, the success of the operation of conversion being entirely independent of the muscular power of the workman, while the finished product being fluid, is readily poured into moulds.

Both the original Bessemer metal, and that now made, if containing a high percentage of Carbon, are practically unweldable, indeed, it is only of late years, since the introduction of the open hearth process and the use of Ferro-Manganese, containing 60 to 80 per cent. of Manganese, that weldable low Carbon steel has been regularly produced, and even now it is much less weldable than wrought iron, and is quite unsuited for "piling." The building-up process is consequently impossible, and the manufacturer must start with a piece in excess of the weight of the finished article.

Steel must not be raised to a welding heat or it will be "burnt" and rendered rotten, high Carbon steel being hopelessly ruined at temperatures very considerably under that point, and in the early days of steel-making much of the new metal was thus seriously damaged by men accustomed to heating iron; provided the mill is strong enough, steel can be rolled at very low heats compared with iron, and a high temperature is a matter of much less importance. The large masses in which steel is now usually handled cool very slowly, and consequently the converters or melting furnaces are placed at a considerable distance from the mills in a separate department by themselves, and the mills are best in a separate but adjoining building, thus keeping the works cooler with considerable advantage to the men employed; in short, ample space round everything to permit of ready inspection and repairs, and to allow of material being rapidly handled, and rolls changed, is the primary essential in laying out a steel works where long and heavy bars have to be produced.

Although the manufacture of wrought iron is easily carried on in small quantities at a time, and there has, therefore, never been the same incentive for employing elaborate machinery in its production, as there has been in the case of steel, it does not necessarily follow that there is any inherent impossibility in employing mechanical power in its manufacture more extensively than has been done at present. For instance, the handling of large iron piles between the furnace and the rolls could obviously be conducted by mechanical power, and though mechanical puddling has not so far been conspicuously successful, there is reason to suppose that it is not so much any impossibility of adapting mechanical power to this purpose, which has prevented the matter being pursued to a successful issue, as the fact that on the introduction of the newer metal, steel, the most energetic and original men in the trade, who had the foresight to perceive its possibilities, had their energies diverted towards it, and their abilities directed to perfecting the appliances needed for its production. The making of the older material was thus left in the hands of those disposed to continue in old-established grooves, and when the new material was firmly established there seemed such a probability of its eventually entirely superseding the older metal, that the puddling process was regarded as doomed to extinction, so that capital was not then forthcoming to carry on further experiments, having for their object the improvements of the older process.

It must also be confessed that the obstructionist attitude assumed by the puddlers towards any "new fangled" methods, has had much to do with preventing the introduction of improvements. In many instances better methods are known, which have been or are now in use in some works, but their more extended employment is prevented by the persistently hostile attitude which the workmen display towards them.

Development of the Rolling Mill.—In rolling either iron or steel, there is a certain portion of metal at each end of the bar which is necessarily imperfect and has to be cut-off, representing so much waste. These "crop ends" can, in the case of iron, be readily used again by putting them amongst the puddle bar in the pile, where they produce an improvement in the quality of the bar, but the steel crops will not weld, and must be remelted in an open hearth furnace; in the case of a Bessemer plant the scraps can be used up, but only to a very limited extent, by passing a small portion through the melting cupola, or throwing small quantities into the vessel when there is a "hot blow." The problem of what was to be done with the Bessemer steel rails when worn out, seeing they could not be piled and reworked like iron ones, was becoming a serious question, when the Siemens-Martin process fortunately solved the difficulty. The quantity of crop-ends it is possible to use in the Bessemer process is trifling, and led to the rolling of bars in longer lengths to avoid them as far as possible. For instance, instead of rolling a rail in one length of 36 feet, and cutting 3 feet off each end to form a 30-foot rail, giving two crop-ends per rail, they were soon rolled in lengths of 68 feet and cut up into two rails, thus reducing the crops to one per rail; now they are commonly rolled in lengths of 130 feet, making four 30-foot rails, with a loss of only one end for every two rails, and even occasionally in six lengths, making one crop for every three rails.

Given sufficiently powerful cranes, there is no more time taken in removing a 5-ton ingot than in performing the same operation on the small ingots of about 7 or 8 cwts., which were cast in the early days of the Bessemer process, while the labour cost per ton is immensely less, and the rapid clearing of the casting pit, when fewer ingots have to be handled, adds enormously to the output obtained from the plant.

Rolling in long lengths enables a greater quantity to be got through the mill in a given time, as will be more fully explained later on, and now that the ingots are handled, always largely and often entirely, by machinery, both at the heating furnaces and at the mills, their size is not dependent on

the physical powers of the workman, and, therefore, large ingots can be handled as easily as small ones, the number in this case rather than the weight of the pieces, determining the output of the mill; consequently we find ingots of 3 to 5 tons each are the sizes most favoured to-day, where there are appliances sufficiently powerful to handle them.

What tends now to limit the size of the ingot to its present proportions, is not the difficulty of handling, or even the cost of larger machinery, so much as the fear of liquation if the ingots are cast in such masses as to cool too slowly, and the fact that very large ingots are apt to develop surface cracks as the outer shell contracts, or to develop hollows in the centre as this centre changes from the fluid to the solid state.

The top of the ingot always contains a certain proportion of slag and impurities, and a portion at the bottom where the metal first strikes is also defective, and as these defects tend to form a smaller percentage of the total the longer the ingots, there is an inducement to cast them as long as possible. If too long and thin, however, they are more likely to stick in the moulds, are not so readily handled in the casting pit, and require more space in the heating furnace, these considerations limiting their length, as liquation and the size of the mills, to some extent, limit their cross-section. But the greater the mass of the ingot the longer will it retain its heat; in ingots of any size the centre is generally more or less fluid when the ingot is removed from the cast-iron mould, which has abstracted from it sufficient heat to reduce the outside to a red heat, and if placed between the rolls in that condition the pressure would squirt the fluid centre out over the workmen. But if the ingot is protected, so as to prevent heat escaping too rapidly from the surface, part of the heat will travel by conduction from the centre to the outside, till the temperature throughout is approximately equalised, the ingot thus having the appearance of having heated automatically. The protection needed is given by dropping the ingot into a pit lined with fire-brick, known as a "soaking pit" (see p. 548). As originally devised by Mr. Gjers, no fuel whatever was used to heat these pits, the ingots, provided they were large enough, coming to a good bright rolling heat, without the application of any external heat whatever, but it is now usual to provide a small amount of assistant firing to meet the cooling due to the stoppage on Sundays, or undue cooling of the ingots consequent on any accidental delay at the mill. Of course there is some loss of heat by radiation through the walls of the pits, so that ingots will not remain hot in them indefinitely, but must be continuously replaced by fresh ingots with hot centres. Where an uninterrupted continuity of work can be ensured, which will maintain a regular flow of ingots through the pits, and the ingots are of sufficient weight and cross-section, any additional heating does harm, as the flame causes loss by oxidation, and if carried too far renders the exterior of the ingot hotter than the interior, whereas the opposite is the case if no exterior heat is supplied. In the latter case the rolls can best exert their beneficial action throughout the whole mass.

Much more powerful machinery is required to shape a steel ingot than will suffice to work up the soft puddled balls from which bar iron is made. Nevertheless, steel bars and plates, of such sizes and weights as were not even dreamed of a generation ago, have been sold regularly, for nearly twenty years, at prices comparing favourably with those demanded for small bars and plates of common iron, and steel rails at prices far lower.

This has become commercially practicable only because means have been devised for rapidly and cheaply handling, by machinery, red hot masses of metal, which it would have been far too costly, if indeed possible, to deal with by manual power.

It will thus be seen that all the circumstances in connection with steel manufacture favour the making and rolling of masses as large as can be used, and the greater the weight of the piece to be rolled, the greater is the necessity of supplementing manual labour by mechancial appliances; to this fact are due the numerous alterations which have evolved the mill of to-day, from its direct ancestor, the mill employed by Cort. What these alterations are will be explained in these pages, and if speeds, weights, dimensions, and outputs appear to be unduly dwelt upon, it must be remembered that the subject can only be adequately explained by giving working particulars of this nature.

The method of producing the raw steel has caused a continuous growth in the size and weight of the ingot, requiring corresponding increases in the sizes of the mills needed to handle the larger masses, the weights of which have continuously required more and more mechanical appliances to manipulate them, as they have either got altogether beyond the power of any number of men to handle properly or the cost of the extra labour involved has become prohibitive. The steady growth in the first cost of the mill and its appurtenances, has necessitated higher speeds, to obtain such an output as will give a satisfactory return on the capital expended, the whole stimulated by the continuous demand for reduction in the cost of the finished steel, under the pressure of ever-increasing competition in the trade.

Though these changes are the result of steady growth, the developments have occurred with such rapidity that few, if any, works are to be found, which are provided with all the best appliances in every department. Many old works cannot find room for modern appliances, and the output of otherwise fine plants is often restricted by some weak link in the chain.

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REHEATING.

By J. W. HALL.

CHAPTER XXI.

REHEATING FURNACES.

Coal-fired Furnaces.—Before steel ingots can be worked by the hammer or press, they must be heated sufficiently to render them soft and malleable, and for this purpose, Bessemer naturally employed the furnaces he found in use for heating iron piles. These furnaces were constructed as shown in figs. 292 and 293, in which A is the fire grate, B the fire-bridge, C the hearth on which the material to be heated rested, and D the flue leading to the chimney, E. The floor of the furnace, made of gravel covered with sand, sloped towards the chimney, to enable the slag formed by the Oxide from the surface of the hot metal, combined with some of the melted sand of the hearth, to flow to the slag hole, F, where it ran off through the spout, G, a small fire being usually necessary at the hole, to maintain the slag in a fluid condition. This slag, known as "flue cinder," is sold for use in blast furnaces, where the iron contained in it is recovered by being reduced to the metallic state, in the presence of incandescent coke. The fuel is introduced through the door, H, and the metal to be heated through the doors, I I, while K is the damper placed on the top of the chimney, where it may be kept comparatively cool by the air above it, the fire being regulated by raising or lowering the damper by means of the rod, L.

Such furnaces are open to grave objections. In the first place they can only be worked efficiently with coals containing sufficient Hydrocarbons to give a long luminous flame, and enough Hydrogen to produce the requisite intensity of heat, and the ash must be low enough for the fires not to need frequent cleaning, whereby much heat is lost. The "Black Country" of South Staffordshire owed its pre-eminence in the iron trade, which it so early and so long enjoyed, almost entirely to the possession of a seam of coal of this description 10 yards thick, which was easily mined when modern means for deep mining were unknown; indeed in numerous places it actually cropped out of the surface of the ground.

The fires in these furnaces require careful attention. As the draught necessary for rapid combustion is obtained by the comparatively feeble vacuum created by the column of heated gases in the chimney, the fuel must be in large lumps to allow a free passage for the air sucked in through