ON THE MANUFACTURE OF STEEL, AND THE MODE OF WORKING IT.

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Steel, as generally used in the arts, is a combination of iron and carbon. The purer these elements in steel, the higher are its qualities. The best steel that has ever been made in any age or country is, without question, 'boulat' (the sabre steel of the Tartars). The special qualities of 'boulat,' and especially the markings appearing on its surface, have sent many investigators on a wrong scent; all thought to find the extraordinary qualities of this steel in some special mixtures. Careful analyses have been made, but, to the surprise of all, nothing has been found competent to explain the presence of the characteristic veining. Inasmuch as the veining of 'boulat' is closely connected with its quality, it was attempted to find substances which, being melted with the steel, would produce the markings required. Steel was melted with various metals, with platinum, silver, and so on, and veinings were, no doubt, produced; but in the first place, they were far from having the same regularity and beauty, and secondly, as well as chiefly, the steel produced was always inferior to 'boulat.' The peculiarity of the veining of 'boulat' lies also in this, that if you heat a good specimen of the steel with clearly-marked veining to a bright red heat, and then allow it to cool, it will be impossible to restore the markings, no matter how long you treat the surfaces with acid. The veining, on the other hand, produced by the mixture of metals never disappears, however much the steel may be heated. But if the piece of 'boulat' in which the veining has

disappeared be melted again, then, if certain conditions in the cooling of the ingot are observed, the veining appears again, though of a somewhat different design; and in this manner it is possible to produce or annihilate the pattern several times. The investigations of Anosoff have clearly shown that the problem is solved in the purity of the steel, and he has succeeded, as is well known, in producing the very highest qualities of Eastern 'boulat.'

On a former occasion I spoke of the observations I had made on the ribbons of dead tint observable on the surfaces of steel guns in the lathe. By means of careful daily records of the forging of the gun ingots, I found that these tints appeared in the boundaries between the hot and the cold portions of the ingot being forged; that is to say, always at those points up to which the ingot was pushed into the furnace. The position and appearance of the strips of dead tint always coincided with the position and form of the limit of heating. If a spot so noted by me was afterwards reheated, then the ribbon of dead tint no longer appeared after turning in the lathe. Besides this, some of these ribbons would disappear as a greater or less thickness of metal was turned off; others penetrated right through the mass of the gun, and never disappeared.

It is further remarkable, that although, at times, the transition from the heated to the cold portion of the ingot was so gradual that it was impossible to assign any limit, yet the ribbon of dead tint developed by the turning of the surface of gun, and corresponding to the above ill-defined limit of heating, was so clearly marked, that it was easy to trace its boundaries with a pencil on the surface of the gun. It must be remarked also that

the ribbon has only one well-defined margin, that which was turned towards the cold end of the ingot; the other margin is shaded off imperceptibly into the normal tint *a* of the steel.

Wishing to investigate the effects of the steam hammer on the structure of steel, I heated a $4\frac{1}{2}$ -inch ingot to a bright red colour, and subjected it to two heavy blows of a 5-ton hammer, so that one-third the length was not touched at all, the second third was flattened to 3 inches, and the last received two cross blows, under each of which there was a compression of at least $1\frac{1}{2}$ inch. The ingot was then left to cool in the open air, and on being broken it was found that the appearance of the structure of each of the three sections remained identical, not only to the naked eye, but to the most careful microscopical examination.

I have also drawn attention to the circumstance that, on one occasion, when experimenting on the influence of the temperature to which steel was heated on its hardness in tempering, I ordered a smith to heat a piece of steel to dull red, but he, by mistake, heated it bright red. Wishing to rectify the error, I did not at once plunge the steel into water, but let it first cool down to dull red, and then immersed it. Although the steel was of a quality capable of extreme hardness in tempering, the immersion not only did not make it hard, but actually made it sensibly softer. I have recalled the above circumstances because, in connection with many others, they induced me to investigate the influence of temperature on steel, and formed points of departure for my researches. Space will not allow of my describing my experiments in detail. I must content myself with stating the conclusions to which I have arrived.

If steel melted in a crucible is constantly kept in violent agitation while cooling, agitation violent enough to keep all its particles in motion, then the cold ingot produced will have a very finely crystallised structure; if, on the other hand, the melted steel is allowed to cool in perfect quiet, then the resulting casting will consist of large well-developed crystals. The appearance of these crystals, and generally the tendency to crystallise under these circumstances, will depend on the purity of the steel. As I have already stated, the ultimate purity of the steel consists in that of its two component elements, iron and carbon, and the best steel is composed of only these two elements.

With reference to other elements, the presence of which is supposed to influence the quality of steel, it is impossible to avoid mentioning the opinion of Fremy, who considers nitrogen so essential, not only to the formation, but to the very existence of steel, that he has laid down the proposition that "if the nitrogen is taken away from steel it will cease to be steel" (*Comptes rendus*, vol. LII., April, 1861); and the supporters of this theory go further, and affirm that steel is a union of iron with cyanogen, which can even be seen burning with a violet flame during the process of casting steel! However, up to the present time (1868), the most careful researches of Caron, Marchand, Biot, Boussingault, Rammelsberg, and others, have not confirmed the assertions of Fremy; for on the one hand, nitrogen is found also in soft wrought iron and in cast iron, and on the other, the quantity of nitrogen found in steel is very variable, and bears no fixed relation to the quantity of carbon; and furthermore, it exists in such small quantities as to be less than a tenth part of the carbon. For instance, Bussengol found 0.00057 part of nitrogen in cast steel, and 0.00124 part in soft wrought iron (*Comptes rendus*, vol. LII., p. 1251). On another occasion, he found in Krupp steel 0.00022 part of nitrogen, and in soft wrought iron and in cast steel, 0.00007 each (*Comptes rendus*, vol. LIII., p. 9).

With reference to the influence of different metals on the quality of steel, it is necessary to state that some of them communicate a particular colour, some diminish the tendency to rust, and others, displacing the carbon, enable the steel to acquire very great hardness in tempering, and so on; but the greater number of substances combined with steel, even in the most insignificant proportions, very considerably lower its quality.

For example, the malleability of steel, being in direct relation to the quantity of carbon contained in it, is materially lowered by the presence of foreign substances. Bessemer steel No. 1, containing 2 per cent. of carbon, is hardly malleable (Boman, "Das Bessemer in Schweden," 1864); whereas, according to Anosoff, pure steel retains its malleability with 3 per cent. of carbon, forming the hardest 'boulat.' Speaking generally, all the efforts of

metallurgists to obtain the highest qualities of steel should be directed to separating impurities from the raw materials, so that the produce of their operations should be a combination of iron and carbon; and all the specifics and nostrums forming the subjects of so-called secrets will be found to consist, in effect, not in the introduction of new materials, but in purifying the raw, and, only as a last expedient, driving out pernicious impurities by means of substances less harmful.

It may as well be said that tungsten steel has not proved a dangerous rival to carbon steel. The fact is that tungsten, when steel containing it is heated, gradually oxidises, at first on the surface of the ingots, and then by degrees to the very centre, so that after a few heats the steel loses its peculiar qualities. This oxidation takes place even at ordinary temperatures.

As I have already stated, steel, cast and allowed to cool quietly, assumes a crystalline structure. If you heat such an ingot to a bright red heat, and allow it to cool without working it in any way, then, on breaking the mass, you will find that its structure has been altered. In order to explain the law regulating the change of structure produced by heating, I draw a line, on which, as on the scale of a thermometer, I shall mark certain points, corresponding to several determined temperatures.

Let the point *o* be the zero of the thermometric scale: *a* marks the temperature of dark cherry-red; *b* red, but not sparkling; and *c* the melting point of a given sample of steel. The points *a*, *b*, and *c* have no permanent place on the scale, but vary with the quality of the steel (in pure steel this variation depends directly on the

quantity of carbon contained); the harder the steel the nearer these points move to *o*, and the softer the steel the farther off, and,

speaking generally, with varying rates. The limits of these movements are sufficiently narrow, so that an inexperienced eye would hardly discern them. Not having suitable apparatus for measuring the temperatures, I have been compelled to denote them by the colours exhibited in heating, the various shades of which only an experienced eye can appreciate; and it must be added that the colours named have reference only to hard and medium qualities of steel; for in the very soft kinds, nearly approaching to wrought iron, the points *a* and *b* recede very far, so that, for example, in wrought iron the point *b* corresponds to white heat.

The definition of the point *a* is as follows:—Steel, however hard it may be, will not harden if heated to a temperature lower than *a*, however quickly it is cooled; on the contrary, it will get sensibly softer and more easily worked with the file. Not having time to enter into the explanation of this phenomenon, I will refer to the investigation of Jullien (*“Les affinités capillaires et les phénomènes de la trempe mis en présence,”* Paris, 1866) on tempering in general: from which he deduces the very probable conclusion that steel, in cooling from a red heat, appropriates a certain amount of latent heat, the quantity of which is directly dependent on the rate of cooling; so that the quicker the steel is cooled, the greater quantity of latent heat it will contain; but if the rate of cooling diminishes below a certain limit, then the latent heat all escapes, and no hardening can take place. The actual hardening Jullien explains by the supposition that the carbon assumes an abnormal crystalline condition. I will add from myself that all this takes place only when steel is heated above the point marked *a* on our scale. The definition of the point *b* is that steel heated to a lower temperature than *b* does not change its structure, whether cooled quickly or slowly. This expression however must be taken conditionally, because steel, during long periods of time, and especially under the influence of shocks or vibrations, and at ordinary temperatures, but to a less extent than wrought iron, changes from the finely granular to the coarse crystalline structure; and as regards the heated, and therefore softened,

condition, and especially at temperatures approximating to that indicated by the point *b*, it is probable that, with the greater facility of motion, the change of structure will take place more rapidly. In my own experiments I have kept pieces of steel at temperatures near to *b* for about eight hours, but after cooling slowly in hot sand I have been unable to detect any change of structure.

As soon as the temperature has reached the point *b* the substance of steel quickly passes from the granular (or, speaking generally, crystalline) condition to the amorphous (wax-like structure), which it retains up to its melting point, that is, to the point *c*. In this condition steel possesses the property of incompressibility, and, at the same time (with respect to the permanence of the amorphism), has an analogy to an exceedingly concentrated solution of a strongly crystalline salt. To make my meaning clearer, imagine a piece of crystallised alum put into a beaker and carefully heated. On attaining a certain determined temperature the piece of alum will appear as if damp, the separate crystals forming the mass will seem, as it were, to be sticking or clinging to each other, forming a mass on the point of melting and which actually becomes gradually fluid, and forms a solution of the crystals of alum in their own water of crystallisation. Now if this fluid mass is allowed to cool it will again crystallise, and according to the conditions under which this cooling takes place we can obtain any quality of crystals, from the coarsest to grains so fine as to be scarcely perceptible to the naked eye.

If the fluid is allowed to cool very slowly, and in perfect quiet, then large regular-shaped, well-developed crystals will be formed; but if, with the same gradual cooling, the liquid is kept in constant agitation (shaken up), the crystals will come out very small. Allowed to cool quietly but rapidly, the crystals will also be small; and, finally, the least favourable condition for crystallisation is when the liquid cools rapidly, and is at the same time violently agitated. In a word, all depends upon the greater or less *time* and the greater or less freedom of motion the particles possess among themselves for collection into crystals; the first condition depends

upon the rate of cooling, the second, upon quiet and the greater or less density (thickness) of the mass undergoing crystallisation.

The same changes take place in the structure of steel heated above the point *b*. The higher steel is heated, the softer it becomes; the greater therefore is the liberty its particles possess to group themselves into crystals (if the quiet of the mass is not disturbed by extraneous forces); and the slower the temperature is suffered to fall to the point *b*, the more time they have for the purpose. At temperatures lower than *b*, as already stated, the structure of the mass does not alter. In this case the action of carbon on iron may be likened to that of water of crystallisation on its salt; that is, it may be supposed that carbon at the temperature *b* begins to dissolve iron just as the water of crystallisation at certain temperatures commences to dissolve the solid substance of the salt. This hypothesis receives confirmation in the process of cementation, in which the iron must be heated to above a certain temperature or no effect will be produced, no matter how long the bars remain in contact with the carbon; it is very probable that the temperature at which carbon begins to be absorbed in cementation is very near to the point *b*.

The power of steel to become granular may be graphically illustrated thus:—On our scale of temperatures *o*, *a*, *b*, *c*, a curved

line rises from the point b , and the ordinates y y , &c., of this curve represent the degree of development of the grains for the corresponding temperatures x x , &c., which become the abscissæ, but necessarily under similar conditions of cooling from the several temperatures x x to the temperature b . At some temperature X lower than the melting point c , the ordinate Y becomes infinite, and an asymptote to the curve, the practical significance of which is apparent in the well-known fact that steel will not endure a high welding heat, but falls to pieces in the fire; and the harder the steel the lower is the temperature at which this takes place, and therefore the nearer is the temperature X to c , and the farther from c .

In manufacturing articles of steel we try to get them as much as possible of a fine-grained structure, especially if strength or toughness is the first object sought. I say that it is better to obtain steel of a finely crystalline structure, because numerous experiments have demonstrated that the greater the preponderance of the crystalline formation, and the larger and more regular the crystals in a given piece of steel, the less resistance does it offer to fracture, the less tenacity does it possess, and therefore men connected practically with the working of steel recognise its qualities by the appearance of its fracture. If the fracture is fine-grained, they say the steel is well forged and consolidated; if it is coarse-grained, it is badly forged and of an open character.

Although we are in the habit of associating with the forging of steel an idea of increased density, yet in reality it appears that, in most cases, forging changes only the form of the steel, and, according to the relations between the force of the blows and the thickness of the piece of steel being worked, hinders crystallisation of the mass to a greater or less degree, but does not increase its density (I am speaking only of forging above the temperature b , such as is general in working large ingots). The force of the blows is too small to vanquish that gigantic molecular force of heat which keeps the particles of steel at a definite distance one from the other. The problem of forging (at temperatures higher than b) consists in this, that while changing the form of the mass of steel

it should have no time to cool and crystallise quietly, but should be kept in the amorphous condition till such time as the temperature sinks below the point *b*, after which, if left to cool in quiet, the mass will no longer crystallise, but will possess great tenacity and homogeneity of structure, so that it will oppose in all its parts a uniform resistance to external forces, of course supposing the chemical composition of the mass throughout to be the same.

But if the problem of forging was limited to the above conditions, it is easily seen that working steel under the hammer might be dispensed with, and the required form given at once by casting in suitable moulds, and preventing crystallisation by rapid cooling. In reality however things are very different. The difficulty of forging is aggravated by the circumstance that the cast ingots out of which guns, for example, have to be made are full of pores filled with gas, bubbles penetrating the interior as well as the surface of the mass, and also with scales and cracks due to contraction, so that, as the castings are delivered from the foundry, it would be impossible to make use of them. These bubbles and cracks must be squeezed or pressed together, and this can only be done by powerful mechanical means—by heavy forging. Simply unforged cast steel is neither less dense nor less strong than steel of the same molecular structure, and forged at temperatures higher than *b*. To convince myself of this, I made a number of experiments, first on the density of the two kinds of steel, and found that in most cases forging had diminished the specific gravity; and secondly, I found that the tenacity of the cast steel was in nowise less than that of the forged, provided, as I said before, both have the same structure. To prove this, I took a cast ingot of coarse crystalline structure; I had it cut longitudinally into four parts. One of these parts was turned down in the lathe, and tested in the proving machine. The second piece was heated to bright red, and vigorously forged under a 3-ton hammer, the forging being stopped when the temperature fell to very nearly the point *b*; the specimen was then turned down, and also tested in the proving machine. The third piece was made red hot, very nearly the same temperature at which the forging of the second piece

terminated, and was allowed to cool in the open air without being forged. Having broken a small piece off this last specimen, I found that it had assumed a finely granular structure very similar to that of the second forged specimen. The third sample was also turned down in the lathe, and tested. The three specimens are now before you, and you may judge for yourselves what varieties of structure the selfsame piece of steel may be made to assume. The results of the experiments are given in the following table:—

	Ultimate Strength, in tons per square inch.	Ultimate Extension.	Diameter of Specimen.	Dynamic Resistance per cubic inch, in inch-tons. Ultimate strength × half elongation.
1st. Unforged specimen . . .	Tons. 34·8	0·023	Inch. 0·885	Inch-Tons. 0·4
2nd. Vigorously forged specimen	41·5	0·053	0·85	1·1
3rd. Not forged, but made finely granular by heating . . . }	38·7	0·166	0·63	3·21

I must also remark, that on the fractured surface of the third sample, as you may observe for yourselves, there is a spot of iron occupying about one-sixth of the area, which was undoubtedly the cause of premature fracture, for the appearance of the surface clearly shows that it began at that spot.

In order to establish the propositions I have advanced, it will of course be necessary to institute a complete series of experiments.* As regards trials by bending and breaking under the hammer, an immense number of experiments have convinced me of the correctness of my views.

From what has been said above, you must have perceived that the whole point lies in the structure of the steel, and that for successful forging the heated ingot, after it is taken out of the furnace, must be forged as quickly as possible, so as to leave no spot untouched by the hammer, no spot in which the steel might

* 1875. Since the above was written, numerous experiments at the Abouchoff Works have fully demonstrated the truth of my views.

crystallise quietly, because, as I have said, the heated piece of steel must be considered in an analogous condition to a saturated solution of a strongly crystallising salt, which, the moment it is allowed to cool quietly, develops large crystals. (I repeat that this has reference to temperatures higher than *b*.)

To show how great is the tendency to crystallisation in steel heated up to a high temperature, and allowed to cool quietly even for a short time, I have brought some specimens by which you can judge of this tendency. The larger specimen was obtained under the following circumstances: an ingot of soft steel prepared for forging was allowed to remain in the furnace for half an hour after it had been heated to a bright orange heat, because the hammer was occupied by another forging. But in order not to overheat the ingot, the smith reduced the temperature of the furnace, and gradually let down that of the work to a bright red. If you will now call to mind what I have said about the tendency of steel to crystallise in cooling between the temperatures *c* and *b*, you will readily believe that during this half-hour the ingot had time to change its internal structure from the amorphous to the crystalline, a change which was greatly assisted by the extreme softening it had undergone at the higher temperature, which presented favourable conditions for the movement of the particles within the mass. As soon as the hammer was at liberty, the ingot was taken out of the furnace, and placed on the anvil; with the very first blow on its middle, the end of the ingot tumbled off from the effects of the concussion; the form of the fracture you can see on the first specimen before you. The remaining samples are taken from other ingots under similar circumstances, and they all show how strongly the crystals have developed themselves; and, moreover, each crystal seems to have formed itself in an independent manner, with so little cohesion to the neighbouring crystals that one shock was sufficient to separate them, and allow the overhanging piece to detach itself by its own weight. The specimens show that fracture has taken place only along the surfaces of the crystals, and nowhere through the body of them.

It might be concluded from the incident above described that the ingot was completely spoiled, and could not be forged again. But such a conclusion would be quite erroneous. It is true that the higher the temperature of the steel, the more susceptible is it to the action of the furnace gases, and the quicker it changes its chemical condition, so that if kept at a high temperature in the furnace it will gradually lose its carbon and be slowly converted into iron (burning). The example I have cited however is only a case of overheating; and in order to know how to correct the mistake made we must turn to the conditions of crystallisation.

Let us again take the beaker of melted alum. Suppose the melting point to be t_0 , and that the solution was further heated up to t_i under which operation it would continue liquid. Let the temperature fall gradually, keeping the solution perfectly quiet, then we shall find that at some temperature t between t_0 and t_i the salt will begin to crystallise; but it is only necessary to shake up the solution to make the crystals dissolve again at the same temperature t . We shall notice also that there is scarcely any cohesion between the separate crystals so formed; and if we do not wish to disturb their mutual relations, we shall have to allow the crystallising solution to cool below the temperature t_0 , and then by a second heating up to t_i we should again receive a fluid mass. The same result would be obtained by a simple single increase of temperature; the difference lies in this, that the liquid produced from the destruction of the incipient crystals in the three cases stated has three distinct temperatures. Applying this reasoning to steel, it is easy to see that, in the case cited, the temperature of the ingot should have been raised again before forging, so as to impart to it an amorphous structure; it should then have been quickly and unceasingly forged all over its extent while the temperature was lowering somewhat, and the tendency to crystallisation decreasing. Or the particles that had commenced to crystallise might have been brought into a motion, corresponding to the shaking of the beaker, but very carefully, so that the crystals formed should not fall to pieces; i.e. the ingot might have been hammered with the very lightest blows; and the

temperature being higher than b , the crystals would have run into each other, the ingot would have assumed the amorphous condition, after which it might have been worked like a piece of wax.

It is, of course, better under such circumstances to allow the overheated ingot to cool quietly, then to heat it again, taking care not to allow the temperature to rise too high and give the mass an opportunity of again changing the restored amorphous condition to a crystallised one; the forging will then not require any special precautions, and the ingot will not tumble to pieces.

I now present you with one of many instances of the spoiling of large steel ingots from the causes I have been explaining, and proceeding from a thorough ignorance, on our part, of the material with which we are working.

On cutting off the end of a shaft 25 inches diameter, the shake $a b$ was met with in the position indicated on the sketch. The dotted lines show the form of the forging before the neck was turned. The walls of the cavity were lined with large well-developed crystals, the size of some of which—as you may see by the specimen before you—reached $\frac{1}{2}$ inch, and between the large crystals were interposed smaller ones about $\frac{1}{16}$ inch diameter; the crystals projected only half their height into the cavity, and on breaking the sample at right angles to the crystalline surface, the prolongation of the crystals into the mass of steel could not be traced; the fracture, though crystalline, was of a totally different nature from that forming the surface of the cavity, and similar to that of the mass of the ingot in the same neighbourhood. The surface of the walls of the cavity had a clear unoxidised metallic

appearance, with a silvery lustre, as you see by the specimen. The ingot out of which this shaft was forged was overheated in the manner I have described, and taken out of the furnace when the crystals had already begun to form. At the first blows of the hammer on its end the part *c* which received the full force of the blow was separated from the mass on account of the want of cohesion caused by the crystallisation, and formed the internal inclined plane *a b*; and as the forging proceeded, the outer layers,

being more acted on by the blows, were more extended, and the cavity considerably increased. The fact that on striking the end of an ingot the force of the blow is taken up by the wedge-shaped piece *c* may be easily demonstrated to the eye, because in those places where swelling, compression, or tension follows the blows of a hammer, a dark shade is soon produced by the partial detachment of thin plates of scale. The same result will be arrived at by an analytical investigation of the effect of a blow on *c*.

The appearance of the crystallised surface of the specimen is, as you see, completely analogous to that of every other specimen of overheated steel; the difference lies only in this, that the surface is not oxidised, because the air could not penetrate into the cavity while the shaft was in a heated state.

It is worthy of remark, that if a piece of steel be so greatly overheated as to assume a strongly crystalline structure, and become liable to destruction at the least shock, and be allowed to cool quietly, then the separate crystals, if they have not been separated by external forces while in a heated state, become so joined or grown together that the fracture of the cold piece takes place, not along the surfaces of the separate crystals, but

indifferently through their mass, though the junctions of the fractures of individual crystals generally take place along their planes of adhesion, owing to which such fracture is always very sparkling.

From this it is evident that the close contact of two surfaces of metals of the same nature heated to a higher temperature than b is sufficient to produce union. This is, in fact, welding; and if, in welding, hammering is always necessary, it is only because, in the first place, it is very difficult without hammering to press two pieces one against the other; and secondly, that it is otherwise difficult to free the surfaces to be welded from the slag which alone protects them from oxidation during the heat. Of course the more homogeneous or analogous the structure of the two pieces, the more perfect will be the union; but one of the first conditions is that there should be the fullest contact between the unoxidised metallic surfaces.

Up to the present we have been discussing the forging of steel only at temperatures higher than the point b , and we have stated that the aim of the forge-master must be to change the form of his ingot in such manner as to keep all its particles in constant motion, and so hinder the formation of crystals, which materially lower the tenacity of the steel. Let us now see what circumstances arise in forging below the temperature b .

The fracture of a piece of cast steel presents a rough surface consisting of groups, as it were, of crystalline *débris* (so-called grains) piled one on another, and generally of a very irregular form. Under the microscope it is easy to see considerable interstices between the groups of grains, and, on more minute examination, spaces may be observed between the grains themselves, which form with each other various interlacings and combinations. In a word, steel, under the microscope, has a more or less porous structure, at first sight destructive of any belief in the tenacity ascribed to it. Time will not permit me to enter into details relating to the appearance, size, and arrangement of the grains; it answers my purpose simply to draw attention to the fact that among the grains of steel there are numerous vacant spaces—pores. The question

arises: what becomes of these pores when the steel, being heated up to the temperature b , acquires the amorphous condition? In all probability, during the rise of temperature from a to b , the expansion of each individual grain (formerly in itself a compact body) goes on incomparably faster than the increase of the external dimensions of the piece of steel, so that the period at which it assumes the amorphous condition coincides with the moment when the atoms composing the individual grains, moving away from each other under the influence of heat, fill up these spaces; it is therefore conceivable why steel becomes at this stage incompressible—why it is impossible to increase its density by hammering, no matter how heavy the blows may be.

It is evident from the above reasoning that if we wish to increase the density of steel, to approach its component grains to each other and so bring them to a more energetic cohesion, we must do so when not opposed by the force of heat, that is, only at temperatures below the point b .

Thus, forging at temperatures below the amorphous condition has the important advantages we are in the habit of ascribing to it. We never forge large ingots below the temperature of amorphous structure, and guns never were and never are forged below that point, because for gun steel it lies, as I have already stated, at a dull red heat, that is, within limits below which, with the mechanical means at our disposal, we can produce no effect on large steel masses. It would be necessary to forge small ingots under our largest hammers, and what an exhibition of inadequate mechanical appliances would be presented if a 4-pounder gun were forged under a 35-ton hammer! The practice now is to forge the 4-pounders under the 3-ton, and sometimes the 5-ton hammer, while the 35-ton hammer is used for the 6-inch, 8-inch, and 9-inch guns, in which the diameter of the cast ingot reaches up to 40 inches; but if you picture to yourself such a large mass of steel heated to a non-sparkling red heat, you will perceive that the utmost efforts of the heaviest hammer would remain inoperative—it would be impossible to forge it.

Forging is carried on at points below the amorphous condition, but it is only in very small pieces, and by those who have some knowledge of the influence of heat on steel.

If a cast ingot of any given structure is heated not higher than the point *b*, then in its heated state it will retain its structure. If it was crystalline, then in a heated state it would be composed of the same crystals, which however would be considerably softened. If the piece of steel be forged in this condition, then its crystals or grains, being driven against each other, will change their shapes, becoming elongated in one direction and contracted in another, and the increase of density becomes so considerable that I have found the specific gravity rise as high as 8, which I have never yet found in steel forged at temperatures higher than *b*. This comparatively cold forging communicates to the metal great clearness of ring, it is no longer so easily worked with the file, weak sulphuric acid produces hardly any effect on it, and so on. With regard to its absolute tensile strength, I regret very much that I have been unable to make any experiments; but there can be no doubt that it is very high.

The fracture of such steel has a silky lustre, and under the microscope it is very difficult to trace the limits of the individual grains; they present the appearance of whole groups of waxy little balls squeezed together under a powerful press. If you cut off and polish the surface of a piece of steel so treated, and then immerse it in weak sulphuric acid, after a time a pattern will form on the surface, which presents the appearance of an irregular interlacing of crooked lines, the size of the network depending on the original size of the crystals, the manner of forging, and so on. I have already stated that the tendency to crystallisation, as well as the form of the crystals and their relative positions, depends on the purity of the steel, and the conditions under which the cast ingots are poured and cooled. In the higher qualities of 'boulat,' the tracery developed by acid is of remarkable beauty and regularity.

The cause of the patterns appearing is the various groupings of the crystals during their formation. These crystals have not

the same chemical composition; the lighter parts of the tracery contain much more carbon than the darker parts—a fact which I have demonstrated—and consequently, simultaneously with the grouping of the crystals or grains, there is a segregation of like chemical compounds. If you heat the piece of steel thus marked (damascened) up to the temperature *b*, or a little higher, and allow it to cool again, you will no longer be able to obtain any pattern by the action of acids. From what has been already said, the cause of this must now be quite plain, and I need not dwell on it any longer.

In conclusion, I will show in what manner the properties of a cast-steel ingot may be best taken advantage of.

With respect to forging at temperatures below the amorphous condition, we can only, as I have already stated, make the smallest guns under the largest hammers. We have at present no mechanism capable of dealing with large masses at low temperatures; but if it were possible, there can be no doubt that guns so forged would be of the very best quality, and their reception into the service would be facilitated by the appearance of the patterns brought out by weak acids, because of the close connection which exists between the quality and the appearance of the steel so treated.

To adapt ourselves to the means possessed by our steel works, we must strive to obtain our material as much as possible of a fine-grained structure; and with this view it is necessary, as we have already seen, to heat the ingots to a high temperature, and to keep forging them until they cool down below the temperature *b*, because, by so doing, we shall be giving the work the required form, and at the same time prevent its structure becoming crystalline, but rather make it approach the amorphous condition. But if we examine the circumstances attending the practical application of this rule to the forging of ingots intended for heavy guns, we shall find that, in many cases, it will be impossible to carry it out, and a forging will be obtained the structure of which is far from uniform, and more likely to be coarsely crystalline than fine-grained. We shall attain our object more easily, and with more certainty, if after having given the forging the desired shape, we

alter its structure to the homogeneous amorphous condition by heating it, and then fix that condition by rapid cooling to a temperature lower than b . For this purpose, it is of course necessary to surround the ingot after heating by some rapidly cooling medium.

From what has been said above, it is evident that, with the same rate of cooling, we shall fix the amorphous condition of the steel with the greatest certainty when we exceed the temperature b as little as possible; and for that reason it is well to determine that temperature for each ingot beforehand.

Having therefore heated the finished forging, or better still, the rough turned and bored gun, to a temperature somewhat higher than b —a point which ought to be determined by the pyrometer—let it then be plunged as quickly as possible into the cooling medium, be it water, oil, or what not; and having reduced the temperature of the work to below the point b , allow it to finish cooling gradually, so as to prevent, as far as possible, internal strains due to sudden and unequal contraction.

To show what changes may be produced in the structure of steel by the operations described, I lay before you three specimens. They are all broken from the same piece of steel. The first specimen exhibits the coarsely crystalline, porous structure that characterised the ingot, notwithstanding that it was well worked under the 35-ton hammer. The second sample was heated to a little above a bright red non-sparkling heat, and then allowed to cool in the open air. Comparing the fractures of these two pieces, you perceive the structure is totally different, though offering one surface to the other proves by the fit that the two pieces were at one time united, and that neither piece has been touched by the hammer since they were broken asunder. The third fragment of the same piece was heated to a bright red heat, and then quickly plunged into water, and left till the temperature sank to a reddish-brown heat; it was then taken out and allowed to cool in the open air. The fracture shows that on the external surfaces, for a depth of 0.1 inch the amorphous condition has been completely preserved. In the centre of the piece the mean diameter of the grains, as

measured by the microscope, is 0.0004 inch, while the mean diameter in the first piece was 0.15 inch, and in the second 0.005 inch. To this I may add that to break the first piece one blow of a hand-hammer (? sledge) was sufficient, to break the second required five such blows, and the third piece had to be broken under a steam-hammer, because the strength of the smith was inadequate for the work.

A similar experiment was made with the tire of a railway wagon wheel. A piece of an ordinary tire was broken by a 5-ton hammer into three pieces. One of them was heated to a light red, and then thrown on the floor to cool in the open air to the ordinary temperature. It was then put under the 5-ton hammer, and required four heavy blows to break it, whereas the first piece broke under one blow of the same hammer. The third piece I heated to a bright red heat, plunged it quickly into water, and took it out again when cooled to a reddish-brown heat, and then found that it required five heavy blows of the 5-ton hammer to break it.

Therefore I say that in order to fix the amorphous condition, and thereby to increase the tenacity of steel, it is necessary to plunge it, after heating, into water. It may be cooled in oil, but, in the first place, this is expensive, and, in the next, numerous precautions have to be taken to prevent the oil catching fire. With respect to cooling in water, I must add that the conductivity of hot metal is very small, and that although the external visible parts soon show the desired fall of temperature, yet the central portions remain very much hotter; it therefore requires care, experience, and many precautions to avoid the too rapid cooling of the outer layers, and the consequent development of severe internal strains.

Time will not permit me to treat this subject in greater detail. I can only state my opinion that not only should every gun be subjected to the treatment above described, but also every article made of steel, as, for example, tires, axles, shafts, &c.*

* 1875. A wagon axle treated in the above manner, and cooled in water, withstood twenty-two blows of a half-ton weight falling 14 feet, and remained unbroken.

It follows, from the principles laid down, that any steel article having, from constant work and concussion, lost its original strength, that is, assumed a crystalline structure, as happens to wagon axles, engine shafts, &c., can, by the help of the process above described, be completely restored by having communicated to it, if not an amorphous structure, at least one so finely grained as to be nearly equal to it, and, at the same time, a compactness and tenacity it very likely did not possess when newly taken into service.

I trust that you will now find it easy to understand the circumstances and facts which I brought under your notice at the commencement of this Paper.

I have heard with pleasure, from a friend just returned from England, that at the Woolwich Arsenal they have adopted the practice of heating their steel gun linings, after forging and rough turning, and plunging them into oil; he was unable to give me any details of the operation, as he only noticed it in passing, but the object of the treatment was, he ascertained, to give the steel greater tenacity. It is possible that I may soon obtain information as to the reasoning which led to the adoption of this practice, and I shall be exceedingly pleased if I find it is based on theories similar to those I have had the honour of laying before you this day. With respect to the doctrines I have been advocating, I have been accused of being too bold in my conclusions; but I am prepared to take a still more decisive step, and to announce the opinion, resulting from my observations, that "future investigation into the question of forging steel will not deviate from the path into which we have this day directed it."