Indeed, the least reflection shows that equilibrium — and it is with equilibrium that the phase rule has to do — is a purely qualitative thing, and has no relation to quantity. Let a simple example verify this idea.

In a large chamber *F, G, H, K* (Fig. 80) is placed a steam boiler *B*, with which are connected a mud-drum *C* and a steam-drum *A*. The boiler is filled with water to about level *L*, and, an escape valve being open from *A* into the open air, the temperature of *F, G, H, K* is raised to 100° C. (212° F.). The water boils until all air is expelled. Then this exit valve is closed, so that the system *A, B, C*, is isolated from without, in short so that no steam can escape and no water can be fed in; but the valves

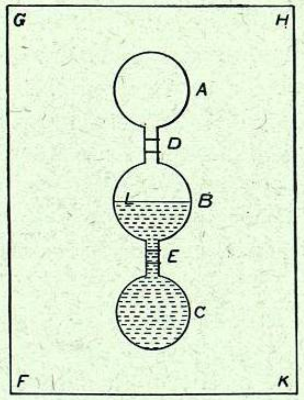

Fig. 80. Equilibrium is not Quantitative but Qualitative.

D and *E* are open, so that the boiler and its drums are in free communication with each other. The temperature is raised to say 121.4° C. (250.5° F.), and the water in *B* evaporates until the pressure of steam (its vapor tension) in the upper part of *B* and in *A* reaches 2 atmospheres (29.5 pounds per square inch). At this pressure and temperature the steam and water are in equilibrium with each other. The further evaporation of water is just balanced by the simultaneous condensation of steam, so that to the eye neither evaporation nor condensation appears to take place.

Now this equilibrium has nothing to do with the quantity of water and steam, or with the proportion between the two, as

is readily seen. Assume that temperature and pressure remaining constant, we close valve *E*; manifestly this will not induce either further evaporation or further condensation; it will have no effect whatsoever. Suppose that now, holding this valve closed, we disconnect this mud-drum *C* and remove it altogether to the outside and destroy it. The quantity of water remaining in the system will be only about one-third as great as originally, while the quantity of steam remains unchanged; the ratio between the quantity of water and of steam has changed greatly, but this change has not in the least affected the equilibrium.

The same would be true if, closing valve *D*, we had removed the steam in the steam-drum *A* from the system; and also if, holding the temperature and pressure constant, we had replaced and reconnected the steam or the mud-drum, or both of them, reopening either or both valves *D* and *E*. Thus we see that no matter what change we bring about in the quantities of water and steam, this change does not affect the equilibrium, provided that temperature and pressure remain constant.

CHAPTER XI. — PROGRESS IN THE MANUFACTURE OF IRON AND STEEL, BETWEEN 1880 AND 1900*

257. SUMMARY. — In the last twenty years of the nineteenth century the world's production of pig iron more than doubled, and that of steel increased fivefold, while that of wrought iron became of secondary importance. The United States passed from the position of the second to that of by far the greatest producer of both pig iron and steel; their production of the former more than tripled, becoming 54 per cent greater than that of Great Britain, and their production of steel increased to more than eight times that of 1880, becoming more than double that of Great Britain,

* Most of this chapter appeared in 1902 as the article on Iron and Steel in the supplement to the *Encyclopædia Britannica* published by the London *Times*. To fit it somewhat to the present work, parts have been omitted, others expanded, still others added, and some of the statistical data have been replaced by later ones.

The Author's sincere thanks are due to the *Times* for permission to reproduce this matter here.

56 per cent greater than that of Germany and Luxemburg together, and 38 per cent of the total for the whole world. In this period the basic open-hearth and basic Bessemer processes rose from mere beginnings to vast importance, each of them now producing in these, the three great iron-making countries, about as much steel as the whole world made in 1880. Of the total production of steel in these three countries in 1899, some 43 per cent was made by the acid Bessemer process, 20 per cent by the basic Bessemer, 16 per cent by the acid open-hearth, 18 per cent by the basic open-hearth — the process in which the greatest development is now to be expected — and only about 1 per cent by the crucible and other minor processes. The production of wrought iron in the United States, which in 1880 was 67 per cent greater than that of steel, is now only about one-sixth that of steel, and wrought iron has practically gone out of use for important objects like rails, and the beams, angles, and other chief parts of bridges and iron buildings, though it will probably long be used for special purposes for which great ease of welding or special ductility is needed.

Delicate methods of research have revealed the nature and constitution of the several varieties of iron. This knowledge has contributed in no small degree to the important beginning which has been made in the use of rational methods of thermal treatment, in which a great extension is to be expected, and it has aided in the discovery and utilization of numerous "alloy" steels.

For armor plate not only has steel completely displaced wrought iron, but alloy steel, which has been specially and differentially carburized, and has received a special heat-treatment, has come into general use. Much the same is true of many other important objects for which the highest quality is needed; thus all armor-piercing projectiles, and many important forgings for engines, especially marine engines, are made of like materials.

Throughout the manufacture of iron and steel those twenty years witnessed great simplification, extension of the use of mechanical appliances, and, especially in the manufacture of the relatively simple products, such as rails, wire, sheets, tubing, beams, etc., a concentration of the industry into enormous establishments, operating on so large a scale as to warrant the use of powerful and costly labor-saving machinery, and the employment

of many highly trained specialists to investigate and watch with the utmost care even the slightest details. In the last ten years of the 19th century alone the cost of labor in many important process was reduced by about one-half, without reducing the rate of wages.

Processes for obtaining wrought iron and steel "direct" from the ore lost their immediate, though not wholly their prospective importance, and at the present time nearly all the ore which is mined is converted into pig iron in the iron blast-furnace. Chiefly by daring, and by the use of more powerful blowing-engines and hot-blast stoves, and of better arrangements for cooling and so protecting the lower part of the furnace, the production of the blast-furnace was increased, until the average production of a single Carnegie furnace to-day, some 200,000 tons per annum, is greater than that of all the United States furnaces in 1830, and ten times that of 1820, and is one-fourth that of the whole world in 1800. By using the waste gases of the blast-furnace in gas engines their importance as sources of power has been greatly increased, so that establishments in which the rolling-mills and other machinery adjoin the blast-furnaces, and therefore can be driven by such engines, will be given a new and often an irresistible advantage over their competitors.

The use of great "mixers" to lessen the irregularities in the composition of the pig iron as it issues from the blast-furnace, enables the Bessemer process to be applied directly to that iron, without allowing it to solidify and thus to dissipate its heat; and this same procedure has come into wide use for the open-hearth process and has even been used tentatively for the puddling process.

The capacity of a single Bessemer converter is now as much as 20 tons, and that of the open-hearth furnace 70 tons, and owing to the car-casting system and other improvements the production of a single pair of Bessemer converters has reached 65,872 tons per month — a rate sixty times that of 1870, and more than four times that of 1880. In some Bessemer works not only is the iron never allowed to cool between its entry into the blast-furnace in the state of ore, and its delivery from the rolling-mill in the form of rails or even of billets, but in this progress it undergoes no true heating by extraneous fuel, save in the blast-furnace itself, for the pig iron furnishes its own calorific power in the

Bessemer converter, and the only other furnace treatment, that of "soaking," merely equalizes the heat of the ingot, and prevents its escape without adding to it.

258. Alloy Steels have come into extensive use for important special purposes, and a very great increase of their use is to be expected. The chief ones are nickel steel, manganese steel, chrome steel, molybdenum steel, and tungsten steel. The general order of merit of a given variety or specimen of iron or steel may be measured by the degree to which it combines strength and hardness with ductility. These two classes of properties tend to exclude each other, for, as a general rule, whatever tends to make iron and steel hard and strong, tends to make it correspondingly brittle, and hence liable to break treacherously, especially under shock. Manganese steel and nickel steel form an important exception to this rule, in being at once very strong and hard, and extremely ductile.

259. Nickel Steel, which usually contains from 3 to 3.50 per cent of nickel and about 0.25 per cent of carbon, combines very great tensile strength and hardness, and a very high limit of elasticity, with great ductility. Its combination of ductility with strength and hardness has given it very extended use for the armor of war-vessels. For instance, following Krupp's formula, the side and barbette armor of war-vessels is now generally if not universally made of nickel steel containing about 3.25 per cent of nickel, 0.25 per cent of carbon, and 1.50 per cent of chromium, and is deeply carburized on its impact face. Here the merit of nickel steel is not so much that it resists perforation, as that it does not crack even when deeply penetrated by a projectile.

The combination of ductility, which lessens the tendency to break when overstrained or distorted, with a very high limit of elasticity, gives it great value for shafting, the merit of which is measured by its endurance of the repeated stresses to which its rotation exposes it whenever its alignment it not mathematically straight. The alignment of marine shafting, changing with every passing wave, is an extreme example. Such an intermittently applied stress is far more destructive to iron than a continuous one, and even if it is only half that of the limit of elasticity, its indefinite repetition eventually causes rupture. In a direct comparative test the presence of 3.25 per cent of nickel increased nearly

sixfold the number of rotations which a steel shaft would endure before breaking.

Nickel steel has been used tentatively for railroad rails; but while it has the stiffness and resistance to wear which they require, too many rails have broken in use. We may hope that this treacherousness will be prevented.

Figs. 81 and 82 give the tensile strength and the ductility of many specimens of nickel steel from various sources, chiefly, however, from M. Dumas' important monograph.* The curves here given are taken from his work (pp. 18 and 19). A rough resemblance to the manganese steel curves (Figs. 83 and 84) may be noticed. The great increase of ductility in case of manganese steel in the 13 per cent manganese region, is reflected in case of nickel steel by a like and very abrupt rise at about 25 per cent of nickel. Again, as the high-ductility region in case of manganese steel is also a region of high tensile strength, so is it also in case of nickel steel.

260. Manganese Steel. — As actually made, manganese steel contains about 12 per cent of manganese and 1.50 per cent of carbon. Although the presence of 1.50 per cent of manganese makes steel brittle, and although a further addition at first increases this brittleness, so that steel containing between 4 and 5.5 per cent can be pulverized under the hammer, yet a still further increase gives very great ductility, accompanied by great hardness — a combination of properties which, so far as I know, was not possessed by any other known substance when this remarkable alloy, known as Hadfield's manganese steel, was discovered.

Its ductility, to which it owes much of its value, is profoundly affected by the rate of cooling. Sudden cooling makes the metal extremely ductile, and slow cooling makes it brittle; its behaviour in this respect is thus the opposite of that of carbon steel. Its great hardness, however, is not materially affected by the rate of cooling.

It is used extensively for objects which require both hardness and ductility, such as rock-crushing machinery, railway crossings, mine-car wheels, and safes. The burglar with his blow-pipe "draws the temper," *i. e.*, softens a spot on a hardened carbon steel or chrome steel safe by simply heating it, so that as soon as

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* "Recherches sur les Aciers au Nickel à Hautes Teneurs," M. L. Dumas, Paris, 1902.

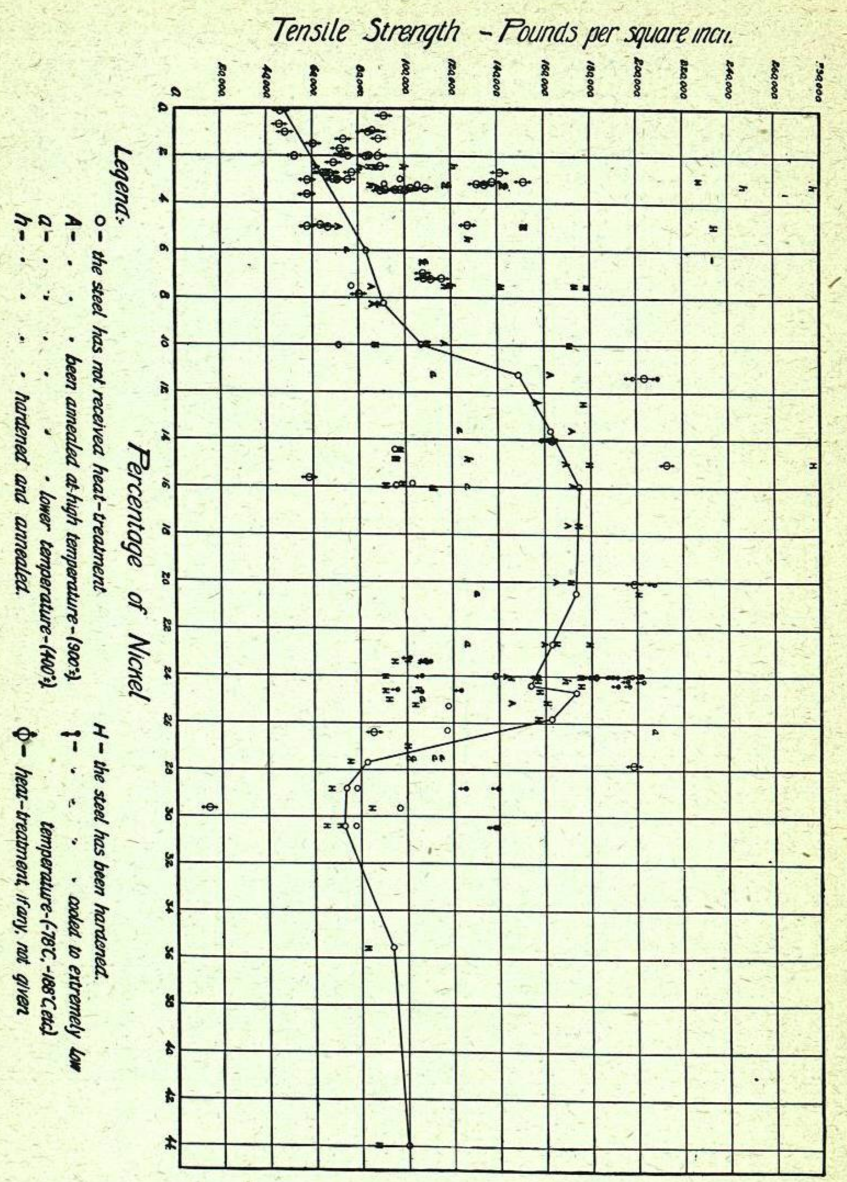

Fig. 81.

Influence of the Proportion of Nickel and Varying Heat-treatment upon the Tensile Strength of Nickel Steel.

NOTE.—The curve here plotted is that given by M. Dumas, *loc. cit.*, p. 18.

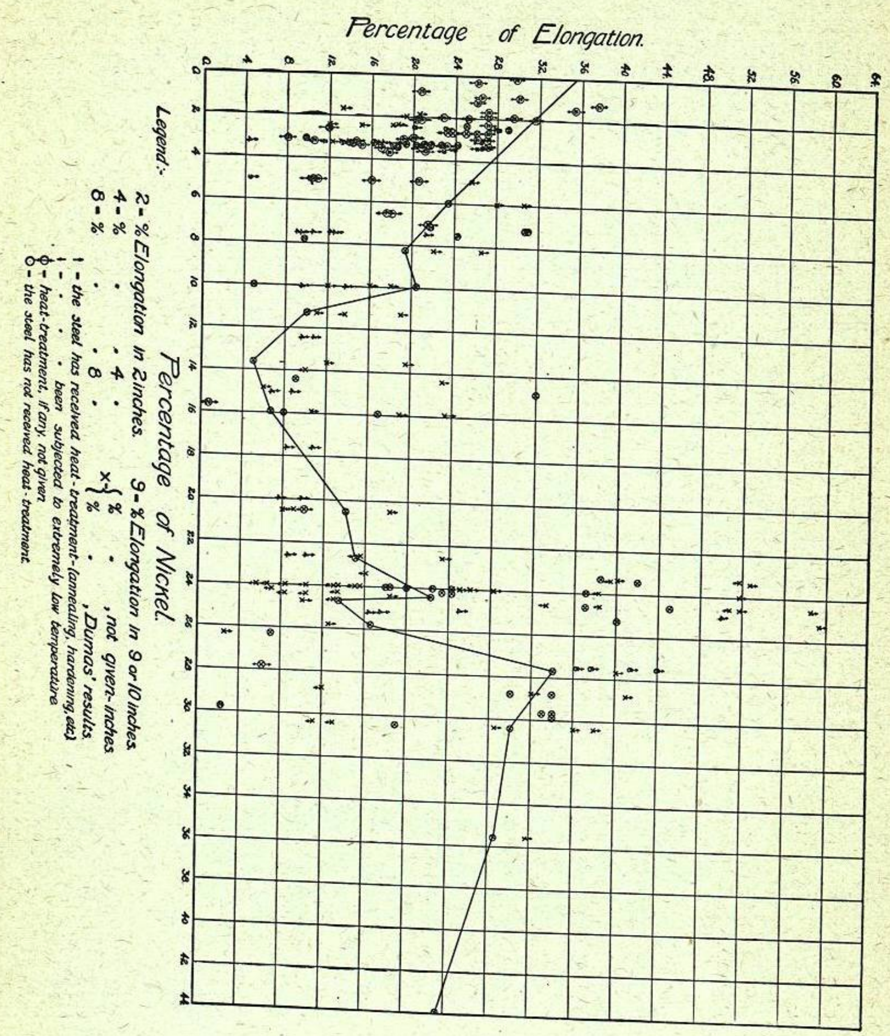

Fig. 82.

Influence of the Proportion of Nickel and Varying Heat-treatment upon the Ductility of Nickel Steel.

NOTE.—The curve here plotted is that given by M. Dumas, *loc. cit.*, p. 18.

it has again cooled he can drill through it and introduce his charge of dynamite. But neither this nor any other known procedure softens manganese steel. This very fact that when cold it is unalterably hard has, however, limited its use, because of the great difficulty of cutting it to shape, which has in general to be done with emery wheels instead of the usual iron-cutting tools. Another defect is its relatively low elastic limit.

Fig. 83 shows the remarkable increase of tensile strength which occurs when the manganese rises from 7 to 13 per cent, and the decline of tensile strength as the manganese increases still farther. By the contrast between the position of the crosses and the black dots it shows also the remarkable effect of sudden cooling.

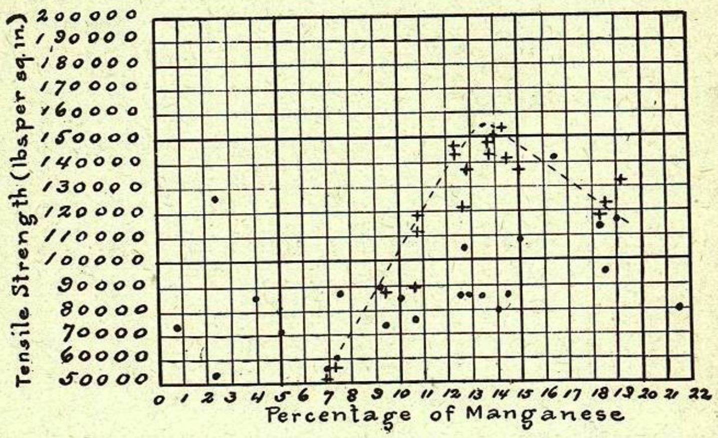

Fig. 83. Influence of the Proportion of Manganese on the Tensile Strength of Manganese Steel.

Legend:
• = Slowly cooled manganese steel.
+ = Water-toughened or suddenly cooled manganese steel.

Fig. 84 shows the corresponding changes in ductility. To show that the maxima for tensile strength and ductility coincide the tensile strength curve sketched by eye in Fig. 83 is reproduced in Fig. 84.

In Fig. 85 is shown the degree to which manganese steel combines tensile strength with ductility, and in Fig. 86 the degree to which it combines ductility with elasticity. These combinations are often taken as a rough measure of the general degree of excellence of a metal for engineering purposes. For comparison the corre-

sponding properties of carbon steel are shown by small black dots, which fall in a pretty well defined band, much below the manganese steel crosses.

These comparisons may, however, give a false idea of the ductility of manganese steel. If two metals elongate in a like manner, the extent of their elongation may be a fair comparative

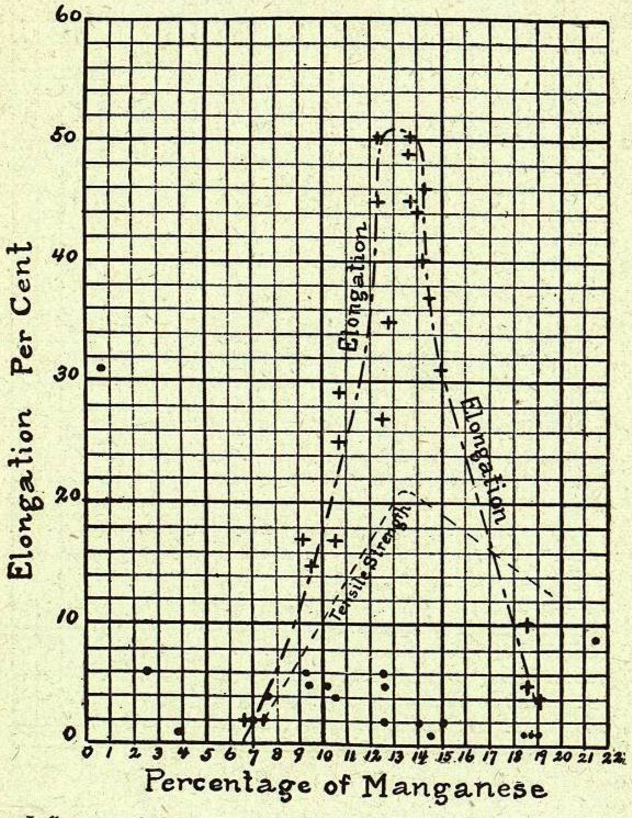

Fig. 84. Influence of the Proportion of Manganese on the Ductility of Manganese Steel.

Legend:
• = Slowly cooled manganese steel.
+ = Water-toughened or suddenly cooled manganese steel.

measure of their ductility; not necessarily so, however, when their mode of elongating is unlike in kind. A bar of carbon steel habitually yields by "necking" when pulled in two, contracting greatly just about the place where rupture occurs, while a bar of man-