which is sandwiched between the comparatively purer metal of the outer walls and the comparatively pure metal at the centre. This general formation is retained in the finished rail, the outside and centre being the purest, with a band of segregated metal between them.

Figs. 258*d* and 258*e* illustrates the general structure of the ingot and the finished rails, and an analysis taken from the outer envelope, the dark segregated ring and the central portion gave the following results :—

	Outer Envelope.				Darker Ring.				Central Portion.			
	C.	S.	P.	Mn.	C.	S.	P.	Mn.	C.	S.	P.	Mn.
Average,	0·62	0·058	0·029	0·74	0·69	0·077	0·035	0·78	0·48	0·041	0·022	0·72

Drop and other mechanical tests made on a number of these rails gave excellent results. From a theoretical standpoint, a rail which has the normal material as cast on the outside, in the centre a relatively soft core, and hardest and most impure material sandwiched between the two, might be expected to produce a tougher rail than one in which the impure material is concentrated in the centre as in the ordinary rail.

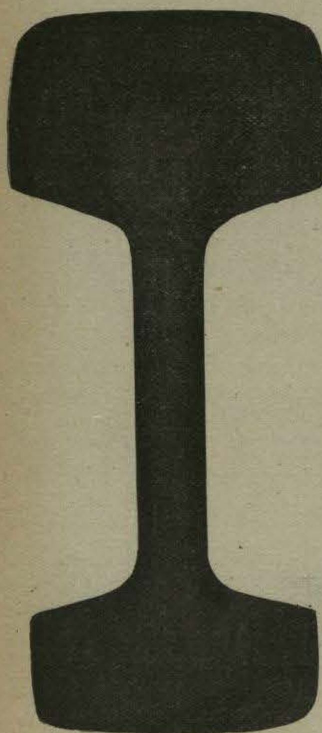

Fig. 258e.

The carrying out of the process in practice presents certain difficulties, and whether it will be possible to control the temperature within such limits that there is no danger, on the one hand, of the ingots being too hot, and the liquid segregate squirting out, and on the other, being too cold so that the pipe is not completely closed up, can only be settled by working a plant continuously on a large scale. Mr. Talbot informs me, however, that his experiments with a large number of ingots since he wrote the paper have demonstrated to his satisfaction that the margin of temperature available is ample for all practical purposes to insure regular results. The details of the plant for carrying out the mechanical squeezing have been largely worked out. Mr. Talbot hopes shortly a plant will be in operation to produce rails on a commercial scale. Should this process be a success, the saving in scrap will be a very important matter, as the yield of sound rails will be increased from 8 to 10 per cent. compared with those rolled from the ordinary ingots.

Cracks.—The cracks in ingots which arise from unequal contraction of the ingot in the moulds, may be either longitudinal or transverse. If through careless teeming, or any irregularity in the surface of the mould, the molten steel

"seizes on" at different levels, this will probably produce transverse cracks, as the ingot itself is contracting and the mould is expanding, and hence the tendency is to tear the surface. If the exterior or shell of the ingot is also cooled much more rapidly than the interior, the rapid contraction of the steel is liable to cause cracks on the surface. As rapid cooling of the outside of an ingot may be the cause of cracks, so if a cold ingot is placed in a hot furnace the rapid expansion of the exterior compared to the interior may cause internal cracks, and in some cases ingots will split quite in two from this cause. It is therefore desirable, whenever possible, to charge the ingots while hot into the furnace, or, in cases where it is necessary to charge them cold, the furnace should be at as low a temperature as possible, and be gradually heated up ; this is especially important with high Carbon steel.

CHAPTER XVII.

SPECIAL STEELS OR STEEL ALLOYS.

Hitherto we have considered steel as consisting almost entirely of iron combined with more or less Carbon, and containing a certain proportion of Manganese. We will now consider shortly the properties of certain special steels, that is of steels which result from mixing with iron other metals with or without Carbon.

Iron alloys readily with most metals, so that the number of steels of this nature which can be produced is necessarily large, moreover it has been found that in many cases a comparatively small difference in the proportion of the added metal makes a very considerable difference in the properties of the resulting special steel. Hence it is easy to see that the field is a very large one, and one that has not yet been fully developed.

In the following pages we shall deal only with the better known of these alloys, some of which are already of the very greatest commercial importance, and with others which are evidently destined to become so as our methods of manufacturing them improve.

The metals which chiefly influence the properties of steel, when admixed with it, may be arranged in a descending scale, as follows :—Manganese, Nickel, Chromium, Titanium, Tungsten, Aluminium, Vanadium, Boron, Uranium, Copper, Tin, Zinc, Bismuth, Lead. Other metals, such as those of the Cerium group, the heavy Platinum metals, etc., doubtless have a very marked effect upon steel when properly introduced into it, but in most cases the field is at present entirely unexplored, or the cost of the added metal renders the resulting alloy too expensive for commercial use.

In this chapter we have taken the alloys formed by steel with other metals in alphabetical order as being most convenient for reference. Copper, tin, zinc, and bismuth are dealt with in the previous chapter, as they are never purposely added, but only occur accidentally as impurities.

Aluminium is usually added to steel, not with the object of forming an alloy, but because of the specific action which the metal has been found to exert on molten cast steel. All steel when in a molten state may be considered to be more or less oxidised, and to contain a greater or less amount of dissolved Iron Oxide, which diminishes both its fluidity and its strength. As this oxidised metal cools, the Oxide, under the action of Carbon, is partially reduced, giving rise to the formation of Carbon Monoxide gas. The gas so evolved causes a more or less violent ebullition in the molten metal, giving rise to unsound ingots containing the well-known "blowholes." The addition of very small amounts of metallic Aluminium to such metal is found to greatly facilitate the flow of the molten metal from the ladle, to stop the violent evolution of gas, and to allow of the production of sound ingots without blowholes. The explanation of this action appears to be that Aluminium has a far greater affinity for Oxygen at high temperatures than iron has, the Iron Oxide being consequently reduced, while the Alumina formed passes out of the metal as slag.

A small addition of Aluminium is found to stop, not only the evolution of Carbon Monoxide from molten steel, but also the evolution of other occluded gases, Nitrogen and Hydrogen. The cause of this action is a little uncertain, but it is supposed that the de-oxidation of the molten metal increases its power of retaining occluded gases, and that when the Iron Oxide is reduced by the addition of the Aluminium, the metal is able to retain in solution gases that would otherwise be expelled.

Aluminium is almost always added to the metal when it is being tapped from the furnace or converter, and is usually thrown into the ladle. The amount added is small, in the case of open hearth steel from 2 to 5 ozs. per ton, and in the case of Bessemer steel some 6 to 8 ozs. When Aluminium has been added the surface of the ingot or casting is found to be smoother.

Aluminium steel has been thoroughly investigated by Sir Robert Hadfield, to whose indefatigable labours we are so largely indebted for our knowledge of the alloys of steel with other metals. The student will do well to consult his original paper read before the Iron and Steel Institute in 1890.* According to this investigator it is doubtful whether Aluminium increases the fluidity of properly made steel. If it does indeed do so the increased fluidity is probably not due to real lowering of the melting point, but to the removal of the Oxide of Iron.

Aluminium above about ·5 per cent. causes the metal to become quite thick and "creamy" and to set quickly, an effect probably due largely to the entanglement of Alumina in the metal as slag.

Hadfield's results show that up to about ·85 per cent. Aluminium, the *cast* annealed samples bent double, cold; unannealed tests did not give so good a result. Increased percentages of Aluminium distinctly reduced the toughness, both in the annealed and unannealed samples. With two exceptions all specimens were sound but not more so than Silicon steel of corresponding percentages.

The addition of successive amounts of Aluminium to iron does not materially affect the hardness, the effect of Aluminium in this respect resembling that of Silicon. As regards *fracture*, Aluminium in the case of cast specimens opens the grain—*i.e.*, increases the size and coarseness of the crystals. In 5 per cent. alloys and upwards the crystals become very large, and cleave somewhat after the nature of Spiegeleisen.

The forged specimens of Aluminium steel, prepared by Hadfield, gave the following results:—

As much as 5·6 per cent. Aluminium may be present before malleability practically ceases: about the same limit as was also found in the case of Silicon steels. The specimens examined were low in Manganese. In Table lxxiii. will be found the chief results obtained from the specimens examined

* *Iron and Steel Inst. Journ.*, 1890, vol. ii., p. 161.

[To face page 394.

...nsile Tests of Ann...

...cific ...vity.	Drillings taken from	How I... Forg...	Appearance of Fracture of ...nealed Forged Bar from which Test Bar was Prepared.	Bending Tests of Annealed Forged Bars $\frac{11}{16}$ inch wide by $\frac{1}{8}$ inch thick.	Welding Tests.	Remarks.
..	Ingot.	Very w...				
..	...		...se fine granular.	Bent double cold.		1. These tests were made with a Whitworth machine.
..	Ingot.	Fairly ...				
..	...		... " "	" "		
...781	Ingot.	Rather...			Would not weld.	
..	...		..e close granular; ...uch closer before annealing.	" "		
..	Ingot.	Very w...				
..	...		..e grain.	" "		
...755	Ingot.	Very w...			"	
..	...		..e close grain; ...uch closer before annealing.	" "		
..	Ingot.	Very w...				
..	...		..e grain.	" "		
...237	Ingot.	Rather...				
..	...		..rser.	" "		
..	Ingot.	Fairly...			"	
..	...		.."	" "		
...554	Ingot.	Fairly...				
..	...		.."	" "		
..	Ingot.	Very s...				
..	...		..se.	16° Broken.		
...726	Ingot.					

[To face page 394.

TABLE LXXIII.—ALUMINIUM STEEL—HADFIELD'S RESULTS.

TENSILE TESTS OF ANNEALED AND UNANNEALED BARS; ALSO, SPECIFIC GRAVITY, FORGING, WELDING, AND BENDING TESTS.

ANALYSIS PER CENT.								Specific Gravity.	Drillings taken from	How Ingot Forged.	Whether Tested in Annealed or Unannealed Condition.	Original Diameter in Inches.	Original Area in Inches.	Limit of Elasticity in Tons per Sq. Inch.	Amount of Stretch in Inches at Elastic Limit.	Breaking Load in Tons per Sq. Inch on Original Area.	Length in Inches on which Extension Measured.	Total Extension per cent.	Reduction of Area per cent.	Appearance of Fracture of Test Bar.	Appearance of Fracture of Annealed Forged Bar from which Test Bar was Prepared.	Bending Tests of Annealed Forged Bars $\frac{11}{16}$ inch wide by $\frac{1}{8}$ inch thick.	Welding Tests.	REMARKS.
Carbon.	Silicon.	Sulphur.	Phosphorus.	Manganese.	Aluminium.	Calculated Percentage of Aluminium.	Loss (Approx.) per cent. of Aluminium.																	
·22	·09	...	...	·07	·15	·25	·10	...	Ingot.	Very well.	Unannealed.	·7979	·50	21·00	...	29·00	2	36·70	62·90	Granular; very dark; a little roaked; smooth on outside.				
...	...	...	...	...	...	...	...	...	...	...	Annealed.	·7979	·50	20·00	...	25·00	2	41·30	63·82	Dark granular; a little roaked; smooth on outside.	Close fine granular.	Bent double cold.		1. These tests were made with a Whitworth machine.
·15	·18	·10	·04	·18	·38	·50	·12	...	Ingot.	Fairly well.	Unannealed.	·7979	·50	23·00	...	30·00	2	37·85	58·18	Dark granular.				
...	...	...	...	...	...	...	...	...	...	...	Annealed.	·7979	·50	20·00	...	26·00	2	40·35	60·74	Dark granular; smooth on outside.	" "	" "		
·20	·12	...	...	·11	·61	·75	·14	7·781	Ingot.	Rather shelly.	Unannealed.	·7979	·50	21·50	...	28·00	2	38·40	54·50	Dark granular; several specks in body.			Would not weld.	
...	...	...	...	...	...	...	...	...	...	...	Annealed.	·7979	·50	18·00	...	25·50	2	40·50	61·98	Dark granular; rough on outside.	Fine close granular; much closer before annealing.	" "		
·18	·16	·09	·03	·14	·66	1·00	·34	...	Ingot.	Very well.	Unannealed.	·7979	·50	20·50	...	29·00	2	33·35	49·86	Dark granular; several long specks in body.				
...	...	...	...	...	...	...	...	...	...	...	Annealed.	·7979	·50	18·00	...	27·00	2	33·00	52·14	Dark granular; rough on outside.	Fine grain.	" "		
·17	·10	...	...	·18	·72	1·25	·53	7·755	Ingot.	Very well.	Unannealed.	·7979	·50	22·00	...	28·00	2	40·00	60·74	Dark granular.			"	
...	...	...	...	...	...	...	...	...	...	...	Annealed.	·7979	·50	18·00	...	25·00	2	47·10	64·86	Dark granular; smooth on outside.	Fine close grain; much closer before annealing.	" "		
·26	·15	·08	·04	·11	1·16	1·50	·34	...	Ingot.	Very well.	Unannealed.	·7979	·50	23·00	...	33·00	2	32·05	51·46	Dark fine granular; smooth on outside.				
...	...	...	...	...	...	...	...	...	...	...	Annealed.	·7979	·50	21·00	...	29·00	2	34·40	53·02	Dark granular; smooth on outside.	Fine grain.	" "		
·21	·18	...	...	·18	1·60	2·00	·40	7·6237	Ingot.	Rather shelly.	Unannealed.	·7979	·50	20·00	...	31·00	2	32·70	52·14	Dark granular; rough on outside.				
..	...	...	...	...	...	...	...	...	...	...	Annealed.	·7979	·50	13·00	...	26·00	2	36·35	67·06	Dark granular; rough on outside.	Coarser.	" "		
21	·18	·09	·03	·18	2·20	2·50	·30	...	Ingot.	Fairly sound.	Unannealed.	·7979	·50	21·00	·0080	31·00	2	22·75	27·80	Crystalline; rather coarse.			"	
...	...	...	...	...	...	...	...	...	...	...	Annealed.	·7979	·50	19·00	·0095	28·00	2	34·87	47·12	Dark granular; fibrous; very rough on outside.	"	" "		
·24	·18	...	...	·32	2·24	3·50	1·26	7·554	Ingot.	Fairly well.	Unannealed.	·7979	·50	21·50	·0085	32·50	2	20·67	24·64	80 per cent. outer circle, crystalline; 20 per cent. inner circle, finer crystalline; rather coarse.				
...	...	...	...	...	...	...	...	...	...	...	Annealed.	·7979	·50	18·50	·0133	28·50	2	33·02	48·62	Dark granular; fibrous.	"	" "		
·22	·20	·08	·03	·22	5·60	6·00	·40	...	Ingot.	Very shelly.	Unannealed.	·7979	·50	None visible.	...	38·00	2	3·67	3·96	Crystalline; lustrous; broke in radius.				
...	...	...	...	...	...	...	...	...	...	...	Annealed.	·7979	·50	27·00	·0050	36·00	2	6·45	6·16	Crystalline; lustrous; broke in radius.	Coarse.	16° Broken.		
·26	·33	·08	·03	·25	9·14	10·00	·86	6·6726	Ingot.							No test; bar made would not forge.								

and in Table lxxiv. the same compared with similar specimens of Silicon steel. It will be seen that up to 2·24 per cent. the annealed samples *bend* double cold, but upon reaching 5 per cent. a great diminution of strength takes place, and annealing practically produces no effect. The *tensile strength* is found not to be increased so much by Aluminium as by Silicon. The increase in the *elasticity* is slight, if any, and it will be seen from Table lxxiv. that Aluminium does not raise the elastic limit so much as Silicon. Generally, Aluminium and Silicon are found to *stiffen* iron but little (as might be expected from their properties), whilst Carbon, Chromium, Tungsten, Manganese, and Nickel increase *rigidity*, as their properties might also lead us to expect. *Hardness* also is not increased in the forged state, any more than in the cast. Forged material containing 5 per cent. Aluminium is very soft, and easily drilled or filed. The action of Aluminium may, therefore, be classed along with that of Silicon, Sulphur, Phosphorus, Arsenic, and Copper as giving no increase of hardness to iron, in contradistinction to Carbon, Manganese, Chromium, Tungsten, and Nickel. Water quenching upon either forged or cast Aluminium steel (in which Carbon is practically absent) seems to produce no effect, the samples when dipped, at even a welding heat, being almost unchanged. When Carbon is present the ordinary hardening action occurs. The *welding properties* of the Aluminium specimens examined (from ·61 to 2·2 per cent. Aluminium) were very poor.

Aluminium, like Silicon, appears to cause a precipitation of Graphite—thus Hadfield found when adding between 3 and 4 per cent. of Aluminium to ordinary Spiegel, that the well-known Spiegel fracture was entirely changed to one resembling ordinary close No. 3 grey pig iron.

Guillet finds that the presence of Aluminium prevents the Pearlite from assuming its ordinary forms, there being a tendency for the formation of little nodules, which are more easily coloured by picric acid.

TABLE LXXIV.—Comparative Table of Forged Silicon and Aluminium Steel, both Materials having been Annealed.

	C.	Si.	Al.	Limit of Elasticity.		Ultimate Stress Tensile Strength.		Extension per cent. on 2″.	Reduction of Area p. cent.	Bending Tests of Annealed Forged Bars.
	Per cent.	Per cent.	Per cent.	Tons per sq. in.	Lbs. per sq. in.	Tons per sq. in.	Lbs. per sq. in.			
Si, Steel A,	·14	·24	...	15·17	34,000	25·0	56,000	37·55	60·74	Bent double cold.
Al, ,, ,,	·15	...	·38	20·0	45,800	26·0	58,246	40·35	60·74	,,
Si, ,, B,	·18	·73	...	19·0	42,560	29·5	66,024	34·02	52·66	,,
Al. ,, C,	·18	...	·66	18·0	40,300	27·0	60,470	33·0	52·14	,,
Si, ,, ,,	·19	1·60	...	25·0	56,000	33·0	74,100	35·0	54·52	,,
Al, ,, F,	·21	...	1·60	13·0	29,100	26·0	58,246	36·35	67·0	,,
Si, ,, D,	·20	2·18	...	25·5	57,120	34·0	76,200	36·50	59·96	,,
Al, ,, H,	·24	...	2·24	18·5	41,440	28·5	62,800	33·0	48·02	,,
Si, ,, ,,	·26	5·53	...	29·0	64,960	39·0	87,400	0·70	2·00	Would not bend.
Al, ,, I,	·22	...	5·60	27·0	60,470	36·0	80,600	6·45	6·16	16° broken.

As regards the application of Aluminium for alloying steel, Hadfield considers that it may find a use for certain special purposes with higher Carbon steels, where Silicon does not seem to act so powerfully in producing soundness as in the case of milder steels with Carbon ·5 per cent. and under. Its special advantages seem to be that it combines in itself the advantages of Silicon and to some extent of Manganese, but as long as alloys containing these elements are so cheap, its extensive use seems hardly probable.

Boron Steel.—Boron in steel seems to have rather interesting properties, although it is doubtful whether any commercial value will ever be attached to the alloys. Messrs. Moissan & Charpy prepared an alloy, of which they give the following analysis :—

Boron, ...	0·58 per cent.
Carbon, ...	0·17 „
Manganese, ...	0·03 „

Traces of Silicon, Phosphorus, and Sulphur.

This material could be rolled out in the form of a cylindrical bar, and could be readily forged at a dull red heat, but crumbled under the hammer when heated too strongly. With such a steel there is a very marked critical point at 1,140° C., equal in intensity to that corresponding with the point of recalescence of hard steel. A rolled and annealed Boron steel which gave a tensile strength of 46 kilos. per square mm. and 11 per cent. extension, gave, after hardening by heating to 1,100° C., and quenching, a tensile strength of 129·5 kilos. per square mm., with an extension of only 3 per cent. As regards its increase of strength by quenching, therefore, Boron steel behaves like high Carbon steel, whilst the diminution of extension is less marked than with the latter. It is remarkable that the hardness of Boron steel (as distinct from its tensile stress) increases but little on heating and quenching. Thus it was found that test pieces having a tensile strength of from 120 to 137 kilos. per square mm. could be filed as easily as those which had not been heated and quenched. This differentiates the action of Boron from that of Carbon in steel on heating and quenching, as the action of Boron seems only to increase the tensile strength without actually hardening the metal.

Chromium.—Chromium is now used to a large extent in the manufacture of steel, both for special qualities and for the production of tires and axles. Chromium is usually employed in the form of Ferro-chromium, which is now a regular article of commerce, and can be obtained of varying percentages of Chromium up to as high as 70 per cent. A refined Ferro-chromium is also on the market, containing 65 to 70 per cent. of Chromium, with only from ·5 to 1 per cent. Carbon. The material is specially useful for high-class tool steel. A still richer product is manufactured containing from 96 to 98 per cent. Chromium, 2 to 3 per cent. iron, ·75 to 1·25 per cent. Carbon, and ·05 to ·75 per cent. Silicon, whilst practically Carbon free Chromium may be obtained by the Aluminium reduction process.

Chromium forms double Carbides with Iron and Carbon, which have been examined by Arnold and Read.* In low Chromium steels containing 0·85 Carbon and up to 3·5 Chromium a double Carbide containing Fe_3C and Cr_3C_2 was found, in medium Chromium steels containing 0·85 Carbon and 3·5 to 15 Chromium a triple Carbide containing Fe_3C, Cr_3C_2, and Cr_4C was found, whilst in high Chromium steels containing over 15 Chromium, Cr_3C_2 disappeared, and a double Carbide containing Fe_3C and Cr_4C was found.

The constitutional diagram of Chrome steels is shown in fig. 258*f*, after Guillet.† From this it is seen that with 0·2 per cent. Carbon the steels are Pearlitic when the Chromium is less than 7 per cent. between 7 and 15 per cent., the steels contain Martensite, and when over 15 per cent. Chromium is present Carbide is found.

Steels containing 0·8 per cent. Carbon and up to 3 per cent. Chromium

* *Iron and Steel Inst. Journ.*, No. 1, 1911, p. 249. † *Ibid.*, No. 2, 1906, p. 7.

are Pearlitic, and consist of Martensite between 3 and 12 per cent., Carbide being found when over 12 per cent. Chromium is present.

The effect of Chromium on steel may be briefly summed up as follows. It does not confer *soundness* on steel, in this respect differing from both Silicon and Aluminium. In small quantities it slightly raises the *tensile strength* of steel without seriously diminishing ductility; when added in too large quantities it induces *brittleness;* both of these effects, however, are modified by the percentage of Carbon present. Hadfield has shown that up to a certain percentage, say ·75, or even 1 per cent., Chromium does not materially affect the product, whether as regards *yield point, tensile strength, hardness test* (Turner's), or hardening qualities by water quenching. Chromium does not materially harden iron, and, in the absence of Carbon, its addition up to 3 or 4 per cent. does not produce any greater hardness than do similar Silicon and Aluminium additions. Carbonless, or nearly Carbonless, Chrome steel does not harden when water quenched.

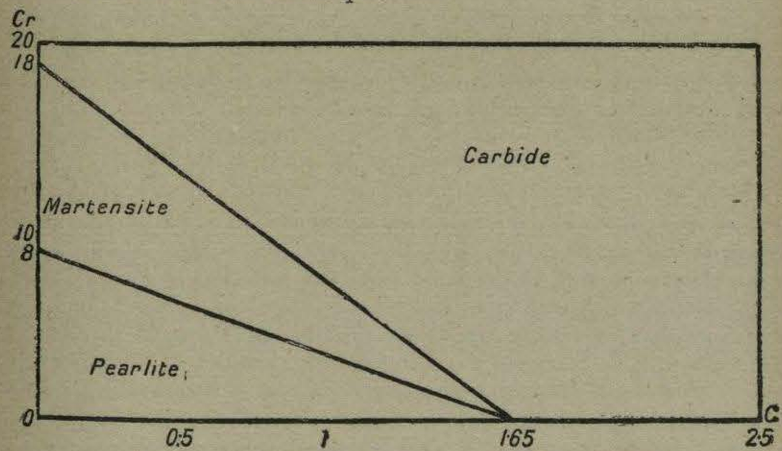

Fig. 258*f*.—Constitutional Diagram of Chromium Steels.

There was a remarkable series of Chrome steels exhibited by MM. J. Holtzer & Cie. at the last Paris Exhibition. The mechanical properties of these steels are shown in the following table, the Carbon being constant at about ·4 per cent. :—

Chromium.	Condition.	Elastic Limit.		Ultimate Stress.		Elongation.	Contraction.*
Per cent.		Tons per sq. in.	Lbs. per sq. in.	Tons per sq. in.	Lbs. per sq. in.	Per cent.	
5	Annealed, . . .	17·8	39,872	31·8	53,760	24·0	0·240
	Hardened and tempered,	48·8	109,312	55·2	123,648	12·0	0·370
10	Annealed, . . .	22·9	51,296	42·0	94,080	21·5	0·440
	Hardened and tempered,	42·4	94,976	54·3	121,632	12·0	0·536
15	Annealed, . . .	25·4	56,896	45·3	101,472	18·5	0·500
	Hardened and tempered,	48·8	109,312	58·1	130,144	11·5	0·546
20	Annealed, . . .	21·2	47,488	36·1	80,864	21·5	0·465
	Hardened and tempered,	27·6	61,824	40·3	90,272	19·5	0·515
25	Annealed. . . .	29·8	66,752	42·2	94,526	18·0	0·621
	Hardened, . . .	27·6	61,824	40·4	90,496	20·0	0·500
30	Annealed, . . .	31·8	71,232	41·6	93,184	19·0	0·620
	Hardened, . . .	28·8	64,518	39·0	87,360	19·0	0·650

The length on which the elongation was measured is not stated, but probably 2 inches.

*Ratio of fractured to original section.

the iron and partly present as double Carbides of Iron and Manganese. The chemical relations of Iron, Manganese, and Carbon have been studied by Arnold and Read,* who showed that well annealed steels containing from 0·41 to 15·11 per cent. Manganese contained the double Carbides, Fe_3C and Mn_3C.

The constitutional diagram of Manganese steels is shown in fig. 258*g*, after Guillet.†

From this it is seen that steels containing 0·2 per cent. Carbon and up to 5 per cent. Manganese are Pearlitic, between 5 and 12 per cent. Manganese, consist of Martensite, and over 12 per cent. of Austenite.

The effect of the Manganese varies with the amount of Carbon present, for with 0·8 per cent. Carbon the steels are Pearlitic with Manganese up to 3 per cent., consist of Martensite between 3 and 7 per cent., and Austenite when the Manganese is over 7 per cent.

We are chiefly indebted to Hadfield for our knowledge of the properties of Manganese steel—that is, steel containing a fairly high percentage of

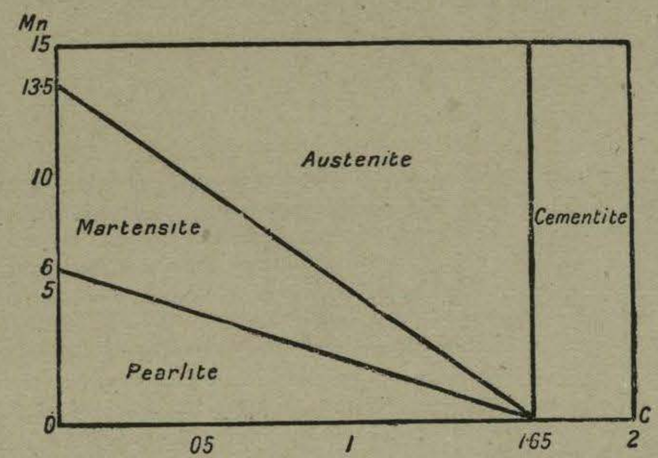

Fig. 258*g*.—Constitutional Diagram of Manganese Steels.

Manganese as distinct from the small amount present in ordinary steel. Before his investigations it was generally believed that steel became brittle and comparatively worthless when the Manganese exceeded 2·75 per cent., and Hadfield found that, provided Carbon did not much exceed 1 per cent., when the Manganese present was increased to over 7 per cent. the result was, for all practical purposes, a new metal, and one which has since become of great value. With from 2·75 to 7 per cent. of Manganese the alloy is brittle, but when the proportion is increased to more than 7 and from this minimum up to about 20 per cent. the result is a metal possessing extraordinary strength and toughness. In ordinary steel it is found that as soon as the Manganese exceeds the usual limits of about ·5 per cent. for mild steel, the tensile strength increases appreciably, the elongation not decreasing so much in proportion as usually occurs in hard Carbon steel. When less than ·2 per cent. Manganese is added to decarburised iron it is very difficult to roll or forge the ingots, but above this they become malleable. Mild steel

* *Journ. Iron and Steel Inst.*, No. 1, 1910, p. 169. † *Ibid.*, No. 2, 1906, p. 6.

containing only ·2 per cent. Manganese is usually unsound and rises in the ingot moulds, the honeycombs, however, closing up more or less on the material being forged, rolled, or otherwise reduced. As the proportion of Manganese increases, the material becomes sounder, but on exceeding 1 per cent. the presence of Manganese begins to be detrimental, the elongation is much reduced, and, in the case of steel castings, they become difficult to anneal. As before stated, the maximum amount which may be present in low-percentage Manganese steel before the steel becomes absolutely brittle and rotten seems to be about 2·5 per cent.

In the cast state Manganese steel, with from 2·5 to 7·5 per cent. Manganese, is extremely brittle, so much so that it can be compared to glass in this respect. The extreme point of brittleness seems to occur at 4 to 5 per cent.; after this a slight increase of strength takes place, but even with about 6·5 per cent. it will only stand the same transverse test as cast iron. The Carbon in these brittle samples is only from ·3 to ·5 per cent. It has been noticed that the more purely the alloy consists of iron and Manganese the more brittle the product becomes. It is extremely hard, approaching dead-hardened steel, and no tool of any kind will touch it. Although so brittle in its cast state, a considerable increase in its strength takes place when hammered or forged, but it is still comparatively brittle and commercially useless.

Above 7·5 per cent. of Manganese, brittleness and extreme hardness begin to disappear, and with forged steel of higher percentages of Manganese, a metal possessing great hardness, and a very considerable elongation is obtained. Thus, Hadfield gives particulars of a specimen of forged material containing 13·75 per cent. of Manganese and ·85 per cent. of Carbon, which, when water-toughened, had a *tensile strength* of 65 tons per square inch with nearly 51 per cent. *elongation*, and another specimen with 69 tons *tensile strength* and 46 per cent. *elongation*. This alloy with about 13 per cent. of Manganese and ·8 per cent. of Carbon is the usual composition of the well-known Hadfield steel.

All these Manganese alloys possess very peculiar hardness both in the cast and forged state, and it is scarcely possible to machine them in ordinary practice; the hardness varies considerably, being greatest in cast state with 5 to 6 per cent. of Manganese and ·3 to ·5 per cent. of Carbon, and gradually decreasing until 10 per cent. of Manganese is reached, which is the softest alloy. The hardness then increases up to 22 per cent. of Manganese, after which the material has more the properties of cast iron, about 2 per cent. of Carbon being present, which obscures the action of the Manganese.

The following table (lxxv.)* gives some of Hadfield's results of the mechanical tests of forged Manganese steels, containing from ·83 to 21·69 per cent. of Manganese.

Manganese steel may be considered for practical purposes wholly *unmagnetisable*.

Steel containing about 1 per cent. of combined Carbon and 14 per cent. of Manganese, is stated to have an electrical resistance thirty times that of copper, and eight times that of wrought iron.

The following figures give the result of analysis made on drillings taken from a cast-steel wheel:—

	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.
Combined	C, 1·150;	Si, 0·551;	Mn, 13·733;	S, 0·043;	P, 0·091.

* *Min. Proc. Inst. Civil Engineers*, vol. xciii.

TABLE LXXV.—HADFIELD'S TESTS OF FORGED MANGANESE STEEL CONTAINING FROM ·83 TO 21·69 PER CENT. MANGANESE.

Mark.	Analysis. Per cent.			Tested in Natural State Specimens, D.			Air-toughened Specimens, C.			Oil-toughened Specimens, A.			Water-toughened Specimens, B.			Remarks.
	C.	Si.	Mn.	Maximum Stress.		Elongation.	Maximum Stress.		Elongation.	Maximum Stress.		Elongation.	Maximum Stress.		Elongation.	
				Tons per sq. in.	Lbs. per sq. in.	Per cent. in 8 ins.	Tons per sq. in.	Lbs. per sq. in.	Per cent. in 8 ins.	Tons per sq. in.	Lbs. per sq. in.	Per cent. in 8 ins.	Tons per sq. in.	Lbs. per sq. in.	Per cent. in 8 ins.	
498,	0·20	0·03	0·83	33	73,900	31	..	..	..	..	..	..	..	..	..	Reduction in area 46 per cent.
41,	0·40	0·15	2·30	56	125,500	6	..	..	..	..	..	..	..	..	..	,, ,, 7 ,,
36,	0·40	0·09	3·89	38	85,400	1	..	..	..	..	..	..	..	..	..	
4,	0·52	0·37	6·95	25	56,000	2	21	47,000	2	19	42,500	2	23	51,500	2	
5,	0·47	0·44	7·22	27	60,500	2	27	60,500	5	25	56,000	3	25	56,000	2	
3,	..	..	7·50	39	87,400	4	..	..	..	..	..	..	..	..	..	,, ,, 9 ,,
7,	0·50	0·28	7·90	..	..	..	28	62,700	8	30	67,900	7	..	..	..	
15,	1·00	0·42	9·15	..	..	..	..	..	..	42	94,000	17	..	..	..	,, ,, 10 ,,
9,	..	..	9·20	40	89,600	6	..	..	..	..	..	..	..	..	..	
6,	0·61	0·30	9·37	33	73,900	5	38	85,400	16	38	85,400	15	39	87,400	15	
11,	0·95	0·21	10·11	38	85,400	5	39	87,400	14	41	91,800	20	..	..	..	
13,	0·85	0·28	10·60	34	76,200	4	41	91,800	17	42	94,100	19	40	89,600	17	
521-6 (lowest),													46	103,000	22	Lowest, highest, and average result given of twelve different tests.
521 (average),	0·72	0·37	10·83	..	..	..	..	..	..	..	..	..	50	112,000	25	
521-10 (highest),													53	118,800	29	
547-iu,	..	..	..	39	87,400	4	..	..	..	..	..	..	..	..	..	
547-7u,													63	141,100	45	Reduction in area 8 per cent. Water-toughened specimens average from 30 to 40 per cent.
547-16,	0·85	0·37	12·29	..	..	..	..	..	..	..	..	..	64	143,400	45	
547-17,													65	145,000	50	
26,	1·10	0·16	12·60	39	87,400	2	37	82,900	11	50	112,000	28	54	121,000	27	
26·0s,	..	..	12·70	47	105,300	6	..	..	..	..	..	..	..	..	..	
19,	0·92	0·42	12·81	39	87,400	5	48	107,500	20	58	129,900	32	61	136,600	37	
552-1,													64	143,400	45	
552-2,	0·85	0·23	13·75	..	..	..	..	..	..	..	..	..	64	143,400	45	
552-3,													66	147,800	49	Still unbroken.
552-2u,													61	136,600	48	
552-5,	0·85	0·23	13·75	..	..	..	..	..	..	..	..	..	64	143,400	50	Bent cold nearly double after being tested.
552-11,													65	145,000	51	
22,	0·85	0·28	14·01	36	80,900	2	48	107,500	14	55	123,200	27	67	150,000	44	Specimen 22 B still unbroken.
196-1,	1·15	0·84	14·27	..	..	..	..	..	..	..	..	..	69	154,600	46	If the load is calculated on reduced area at the time of fracture, it is equal to 102 tons per square inch. Reduction in area 37 per cent.
196-2,	1·15	0·84	14·27	..	..	..	..	..	..	..	..	..	70	156,800	40	
596,	1·10	0·32	14·48	39	87,400	1	49	109,600	5	..	..	..	63	141,100	37	
597,	1·24	0·16	15·06	49	109,400	2	47	105,300	2	..	..	..	61	136,600	31	
598,	1·54	0·16	18·40	51	114,000	1	39	87,400	1	..	..	..	53	118,800	10	
239,	1·83	0·26	18·55	43	96,300	1	..	..	..	..	..	..	55	123,200	5	
619,	1·60	0·26	19·10	52	116,500	1	41	91,800	1	..	..	..	59	132,000	4	
291,	1·90	0·32	19·98	..	..	..	..	..	..	23	51,500	nil.	..	..	..	
235,	2·10	0·46	21·69	36	80,900	9	34	76,200	12	33	73,900	11	..	..	..	

NOTE 1.—The treatment of the bars is indicated by the letters given under the four headings; D = tested as forged; C, A, and B = reheated to yellow heat, and cooled respectively in air, oil, and water.

NOTE 2.—The appearance of the fractured test bars in the specimens from 3 to 9 per cent. is always coarse and granular, but those with more than 9 per cent. and "water-toughened" are silky and fibrous.

NOTE 3.—The tensile tests are given in tons and lbs. per square inch on original area.

NOTE 4.—The Phosphorus and Sulphur are not given (to save space) as they varied very slightly. The Sulphur averaged 0·06 and the Phosphorus 0·09.

This steel was found to be feebly magnetic. It was brittle to shock, and comparatively easily broken by a hammer, but exceedingly hard to drill. It is not improbable that had the Silicon and Phosphorus been present in less quantities, the steel would have been stronger to resist shock.

This Manganese steel possesses the peculiar advantage of being softened and toughened by the following treatment:—A piece heated to about 990° to 1,090° C., on being plunged at this temperature into cold water, is appreciably softened and its toughness is greatly increased. The nearer the above temperatures are approached and the colder the water the tougher will be the material. Hardness is then restored by reheating to a bright red and cooling in air.

The use of Manganese steel is limited by the extreme difficulty experienced in machining it. For alloys from about 12 to 18 per cent. Manganese a great increase of *strength* and *ductility* is obtained by reheating nearly to whiteness and sudden cooling, both the *tensile strength* and *elongation* being improved. With large forgings the improvement brought about by quenching is naturally somewhat counterbalanced by the tendency to crack, caused by internal stresses. Heating and quenching, whilst increasing the tensile strength and elongation, have been found to lower the elastic limit.

Molybdenum.—Molybdenum steels are very similar to Tungsten steels in mechanical properties; Molybdenum, however, is said to be two or three times as powerful as Tungsten in its effect. Giesen * found that Molybdenum steels with 0 to 4 per cent. Molybdenum and 0·3 per cent. of Carbon, or 0 to 2 per cent. Molybdenum and 0·95 per cent. Carbon, gave results approximating closely to those furnished by Tungsten steel in point of tensile strength, elastic limit, elongation, hardness, and brittleness, when the ratio of added Molybdenum to added Tungsten was as 1 : 2·225.

Guillet † states that steels containing 0·2 per cent. Carbon and less than 2 per cent. Molybdenum are Pearlitic, and with more than 2 per cent. Molybdenum contain Carbide, whilst with 0·8 per cent. Carbon they are Pearlitic, with less than 1 per cent. Molybdenum, and contain Carbide with more than 1 per cent.

The Pearlitic steels have a high tensile strength and elastic limit, which increase regularly with the amount of Molybdenum. The elongation and resistance to shock diminish a little, but continue to have high values.

The Carbide steels have a tensile strength and elastic limit which increase with the percentage of Molybdenum; the elongation and reduction of area are low; brittleness increases with the percentage of Molybdenum and Carbon.

Molybdenum steels ‡ have been used for tools, rifle barrels, large guns, propeller-shaft forgings, and wire drawing.

Nickel.—The alloys of Nickel and Iron are very important, and are rapidly extending in use. Nickel in the pure state is a metal somewhat less white than Silver, with a melting point of 1,435° C.

Nickel alloys with Iron in all proportions at a temperature between 1,500° and 1,600° C., and a small proportion of Carbon is said to lower its melting point perceptibly; it is harder than Copper or Iron, but will not take temper on sudden cooling.

Commercial Nickel (from 98 to 99 per cent. Nickel) is not difficult to cast but is *cold short*. Cast bars are likely to be spongy, but after hammering are compact and tough.

* *Iron and Steel Inst.* Carnegie Scholarship Memoirs, vol. i., 1909, p. 31.

† *Iron and Steel Inst. Journ.*, No. 2, 1906, p. 11. ‡ *Eng. Mag.*, vol. xxxiii., pp. 91-98

It has been found that the addition of a very small quantity of pure Magnesium removes from Nickel the occluded gases, and gives a metal capable of being drawn or rolled perfectly free from blowholes. Magnesium in Nickel, like Manganese in ordinary steel, acts as a deoxidising agent, and it improves the ductility and malleability of Nickel to such an extent that the metal may be rolled into thin sheets 3 feet in width.

Aluminium may be used equally well, but if used in excess serves to make the Nickel very much harder. Nickel will alloy with most of the useful metals, and generally increases their hardness, toughness, and ductility.

To show the physical properties of almost pure Nickel in the cast and forged state, we give the following short table from Hadfield's paper on the "Alloys of Iron and Nickel":—*

TABLE LXXVI.

Material.	Condition.	Unannealed.				Annealed.			
		Elastic Limit.	Max. Stress.	Elongation in 2 Ins.	Reduction in Area.	Elastic Limit.	Max. Stress.	Elongation in 2 Ins.	Reduction in Area.
Per cent.		Tons per sq. in.	Tons per sq. in.	Per cent.	Per cent.				
Carbon, 0·08 . . Iron, 99·80 . .	Cast	14	20	16	34	Not obtained.			
Carbon, 0·08 . . Iron, 99·80 . .	Forged	14	22	47	76	9	18	52	76
Carbon, 0·16 . . Nickel, 98·80 . .	Cast	11	16¼	4½	9¾	Not obtained.			
Carbon, 0·16 . . Nickel, 98·80 . .	Forged	14	32¼	45½	57	7	13¼	54	52½

It should be noted that whilst the elastic limit of Nickel is slightly less, its tenacity is nearly 50 per cent. greater than that of iron—viz., 32 tons against 22 tons per square inch.

The following results, kindly supplied by Mr. W. H. S. Shakell, give some further particulars of the mechanical properties of Nickel in the cast, wrought, and rolled condition:—

TABLE LXXVII.

	Maximum Stress.		Elongation.	Reduction of Area.	Remarks.
	Lbs. per sq. in.	Tons per sq. in.	Per cent.	Per cent.	
Rolled plate 8 ins.,	67,760	30·25	31·4 in 8 ins.	31·5	
Cast bar untreated,	30,985	13·84	6·5 in 2 ins.	6·5	
Casting, ...	85,000	37·95	12 ,,	...	
Wrought nickel, .	96,000	42·86	14 ,,	...	Wrought from 2 × 4 ins. to ½ in. square.
Wrought nickel annealed, . . .	95,000	42·41	23 ,,	...	Wrought from 2 × 4 ins. to ½ in. square.
Rolled nickel, . .	78,000	34·82	10 ,,	...	Very hard, not annealed after rolling from 2 ins. to ⅛ in.

* *Min. Proc. Inst. Civil Engineers*, vol. cxxxviii.

A great deal of information has been published on the properties of Nickel steel, Mr. J. F. Hall, of Sheffield, and Mr. J. Riley having been amongst the early workers in this field. The matter has more recently been most thoroughly investigated by Hadfield,* and it is to him that we are chiefly indebted for the scientific examination of the properties of steel containing varying percentages of Nickel.

The following table gives the results he obtained on specimens of Nickel steel in the unannealed and in the annealed conditions, with Nickel varying from ·27 to 49·65 per cent., the Carbon being kept low and approximately equal in the whole series:—

TABLE LXXVIII.

Analysis.			Unannealed Test Bars.						Annealed Test Bars.					
C.	Mn.	Ni.	Elastic Limit per Square Inch.		Tensile Stress or Maximum Stress per Square Inch.		Elongation per cent. on 2".	Reduction of Area per cent.	Elastic Limit per Square Inch.		Tensile Stress or Maximum Stress per Square Inch.		Elongation per cent. on 2".	Reduction of Area per cent.
			Tons	Lbs.	Tons.	Lbs.			Tons	Lbs.	Tons.	Lbs.		
0·19	0·79	0·27	19	42,560	31	69,440	35	56	20	44,800	28	62,720	37	52
0·14	0·75	0·51	20	44,800	30	67,200	36	62	21	47,040	27	60,540	41	63
0·13	0·72	0·95	25	56,000	33	73,920	31	53	20	44,800	27	60,540	41	63
0·14	0·72	1·92	26	58,240	34	76,160	33	55	22	49,280	31	69,440	36	53
0·19	0·65	3·82	28	62,720	37	82,880	30	54	25	56,000	33	73,920	35	55
0·18	0·65	5·81	28	62,720	41	91,840	27	40	28	62,720	37	82,880	33	51
0·17	0·68	7·65	31	69,440	49	109,760	26	42	30	67,200	45	100,800	26	41
0·16	0·86	9·51	42	94,080	85	190,400	9	18	32	71,680	56	125,440	2	2
0·18	0·93	11·39	65	145,600	94	210,560	12	24	45	100,800	89	199,360	12	26
0·23	0·93	15·48	55	123,200	94	210,560	3	2	...	...	68	152,320	1	1
0·19	0·93	19·64	47	105,280	91	203,840	7	6	45	100,800	87	194,880	5	4
0·16	1·00	24·51	32	71,680	77	172,480	13	14	25	56,000	78	174,720	14	8
0·14	0·86	29·07	25	56,000	38	85,120	33	44	16	35,840	37	82,880	48	51
0·16	1·08	49·65	No test made.						15	33,600	36	80,640	49	53

Below are given the mechanical tests of different Nickel steels made from commercial steel for comparison with the specially prepared bars of Hadfield's Nickel steel—combined Carbon about ·2 per cent., and Nickel about 3·2 per cent.

TABLE LXXIX.

Maximum Stress.		Elastic Limit.		Elongation on 3".	Contraction on Area.
Lbs. per sq. in.	Tons.	Lbs. per sq. in.	Tons.	Per cent.	Per cent.
94,185	42·04	58,995	26·31	26·4	60·83
94,245	42·07	60,770	27·12	25·5	68·58
93,215	41·61	58,740	26·22	25·8	61·33
93,730	41·84	60,770	27·12	25·8	59·81
92,410	41·25	59,550	26·58	28·0	60·74

From these figures it will be noticed that the *elastic limit* of 3 per cent. Nickel steel with ·2 Carbon is about equal to the *tensile strength* of ordinary mild steel, while the *elongation* and *contraction of area* are about the same.

* *Min. Proc. Inst. Civil Engineers*, vol. cxxxviii.

Mr. Francis Sperry, Cleveland, Ohio, gives the following results obtained on testing *transverse* specimens taken from a complete set of Nickel steel gun forgings, made by the Bethlehem Iron Company for the Bureau of Ordnance :—

TABLE LXXX.

	Maximum Stress.	Elongation.	Elastic Limit.
	Lbs. per sq. in.	Per cent. in 2 ins.	Lbs. per sq. in.
Tube, . .	93,200	21·2	58,300
Jacket, . .	99,900	20·4	60,000
Hoops, . .	99,100	20·5	68,200

Tests made on 2 ins.; test pieces ½ in. diameter.

Comparing these results with those usually obtained in similar Naval gun forgings made from ordinary Carbon steel, the tensile strength shows an *increase* of about 10 per cent. with an *increase of elastic limit* from 22 to 28 per cent., while the contraction of area and elongation are but slightly reduced.

The great excellence attained by the Greener Gun is attributed to the use of Nickel steel barrels containing about ·2 per cent. Carbon and 2·75 per cent. Nickel, and the U.S. Bureau of Ordnance is said to have adopted Nickel steel for its small arm barrels.

From Table lxxxi. it will be seen that the Nickel steel shows an average increase of about 31 per cent. in elastic limit, and an average increase of about 20 per cent. in tensile strength, without any great alteration in the ductility as shown by the percentage elongation and contraction of area.

The general effect of Nickel upon iron, and the part played by Carbon in such alloys, have been well summed up by Mr. M. C. White, of the Bethlehem Iron and Steel Co., U.S.A., who has had large experience on a practical scale with various special applications of Nickel steel, and whose remarks are quoted in Mr. Hadfield's paper already referred to.

TABLE LXXXI.—Comparative Tests of Nickel Steel and Best Soft Flange Steel, Specimens Cut from the Plates in Both Cases.

	Tensile Stress or Maximum Stress.		Elastic Limit.		Elongation in 8 ins.	Contraction of Area.
	Lbs. per sq. in.	Tons per sq. in.	Lbs. per sq. in.	Tons per sq. in.	Per cent.	Per cent.
1. Nickel steel containing — Per cent.: C, 0·08; Ni, 2·69; Mn, 0·36; Per cent.: S, 0·038; P, 0·045	64,080	28·60	47,100	21·02	23·25	53·0
	66,370	29·62	44,700	19·95	26·00	53·3
	66,000	29·46	47,400	21·16	25·00	56·3
	67,100	29·95	47,300	21·11	24·50	45·1
	64,800	28·92	...	...	26·00	54·4
	66,200	29·55	48,900	21·38	23·75	49·7
2. Soft steel containing — Per cent: C, 0·10; Mn, 0·27; Per cent.: S, 0·039; P, 0·040	55,500	24·77	35,700	15·93	26·00	45·6
	54,500	24·33	35,500	15·84	26·00	45·8
	53,900	24·06	32,800	14·62	27·50	52·9
	52,500	23·43	34,060	15·20	32·00	61·8
	53,700	23·97	34,500	15·40	27·00	63·0
	56,500	25·22	36,900	16·47	26·00	63·0

"The *tensile strength* and *elastic limit* of Nickel iron alloys and Nickel steel rise with increasing proportions of Nickel, reaching a maximum at about 20 per cent. Passing this they begin to fall, and elongation increases abnormally up to about 30 per cent. The *ratio of elastic limit to tensile strength* increases with increasing Nickel, at first slowly up to about 10 per cent., when it makes a sharp rise, and then continues gradually up to 20 per cent., after which the ratio falls away rapidly.

"The *hardening effect* of quenching ceases when about 10 per cent. of Nickel is present, but is quite marked in the lower percentages. In this case the effect is heightened by the Manganese, but with ·06 per cent. Manganese it is still decided. Between 10 and 20 per cent. Nickel, neither quenching nor annealing exerts any decided effect. Above 20 per cent., quenching produces a softening effect, which is decided at 30 per cent. Perhaps it would be better to call it a *weakening* effect, as the tensile strength and elastic limit are much lowered, the elongation increased, but the cutting properties shown by turning in a lathe are not perceptibly changed.

"These results refer to alloys of Nickel and iron containing Carbon from ·06 to ·1 per cent., or practically Carbonless alloys. The Manganese ranged between ·06 and ·1 per cent.

"Nickel tends to check segregation, due probably to the fact that it raises the melting point of the Carbides or cementing material, and causes the whole mass to set more nearly together. This is evidenced by the finer grain of Nickel steel ingots. Nickel does not prevent blowholes, and great care is required in the manufacture to avoid them, as they weld up less easily than in other steels.

"There are many difficulties to be overcome in the handling of Nickel steel as commercially made, where the Carbon ranges from ·15 to ·9 per cent., the Manganese from ·3 to ·9 per cent., and the Nickel from 3 to 30 per cent. It is very susceptible to changes of temperature when containing the usual amounts of Carbon and Manganese, requiring considerable care in heating and working to bring out its best qualities, which are certainly worth all the labour bestowed upon it.

"The fact that Nickel raises the elastic limit of steel is clearly shown by Mr. Hadfield's results, but to give a reason for this effect, which can be definitely proved, would be difficul . The best explanation is that it strengthens the cementing material up to a certain point (20 per cent. Nickel), and holds in a more rigid matrix the iron crystals which in Nickel steel exist in smaller aggregations. Beyond this the cementing material is not so much strengthened as it is toughened, which accounts for the abnormal increase in elongation."

According to Guillet,* steels containing 0·12 per cent. Carbon and up to 10 per cent. Nickel are Pearlitic, between 10 and 27 per cent. Nickel are Martensitic, and with over 27 per cent. Nickel consist of Austenite; whilst steels containing 0·8 per cent. Carbon are Pearlitic up to 5 per cent. Nickel, Martensitic between 5 and 15 per cent. Nickel, and consist of Austenite when over 15 per cent. Nickel is present. The constitutional diagram being given in fig. 258*h*.

In the Pearlitic steels the tensile strength and elastic limit are higher the larger the percentage of Nickel present, and at the same time the elongation, reduction of area, and resistance to shock are not diminished by the presence of Nickel, the hardness, however, is slightly increased.

* *Iron and Steel Inst. Journ.*, No. 2, 1906, p. 4.

The Martensitic steels possess very high tensile strength, very high elastic limits, and low elongations. They are brittle and exceedingly hard.

The steels containing γ-iron possess medium tensile strength, usually low elastic limits, extraordinary high elongations and contractions, a remarkable degree of resistance to shock, and medium (Brinell) hardness.

Arnold and Read * have studied Nickel steels, and show that with steels fairly high in Carbon, and containing up to 8 per cent. of Nickel, the Carbide, Ni_3C, exists only in negligible proportions. With Carbon about 0·8 per cent., associated with 20 to 30 per cent. Nickel, the Carbide, Ni_3C, is present in considerable quantity. These authors conclude that in ordinary structural steels containing up to 7 per cent. Nickel, this element is not associated with Carbon, but is alloyed with the iron and Manganese. They are also of the opinion that there is a definite alloy of iron and Nickel corresponding to the formula Fe_7Ni, and known as Nickelide of Iron, which has very remarkable properties.

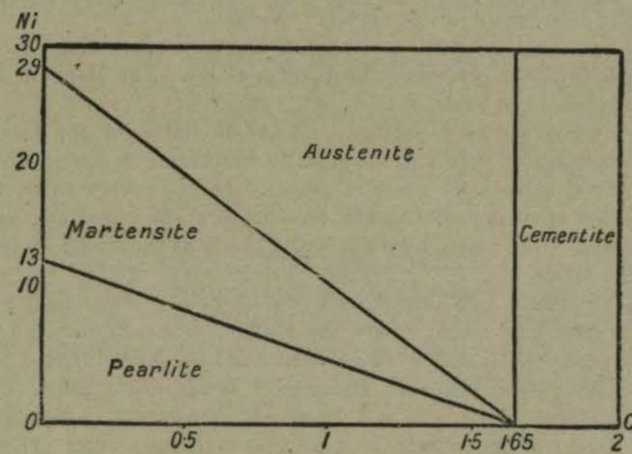

Fig. 258*h*.—Constitutional Diagram of Nickel Steel.

Nickel steel forms an admirable material for forgings for marine and general engineering purposes. From its relatively high tensile strength and elastic limit, without any appreciable reduction in elongation and contraction of area (in comparison with ordinary mild steel), it allows in many instances a considerable margin for reduction in the weight of metal, and consequently a considerable saving in ultimate cost of the forgings.

Welding.—Nickel under 1 per cent. does not appear to affect the welding properties of steel, but above this percentage welding becomes more difficult, though even with 3 per cent. with care good results can be obtained, as shown by the following tests on welded and unwelded specimens containing ·26 per cent. of Carbon and 3 per cent. Nickel. The tenacity with which the film of Oxide adheres to the surface of the metal does undoubtedly interfere seriously with welding, and this difficulty increased with the percentage of Nickel present. It is not advisable to use Nickel steel with over 1 per cent for general welding purposes.

* *Proceedings Institution of Mechanical Engineers*, 1914, p. 248.

TABLE LXXXII.—Comparative Strength of Welded and Unwelded Nickel Steel.

	Carbon.	Nickel.	Maximum Stress.		Elongation.
			Tons per sq. in.	Lbs. per sq. in.	Per cent.
Welded, . .	0·26	3·00	35·22	78·904	16
Unwelded, .	...	...	35·10	78·622	24

Nickel Steel Wire.—Nickel steel containing as much as 30 per cent. Nickel can be drawn into wire as easily as ordinary steel, and wire of this class contains sufficient Nickel to make the non-corroding qualities of the metal prominent, and is well adapted for hawsers and cable service in salt water. A sample of Nickel steel containing ·4 per cent. Carbon and 27·8 per cent. Nickel, said to be used as torpedo defence netting by the U.S. Navy, gave the following physical test :—

Diameter of Cross Section.	Area of Cross Section. Sq. in.	Reduced Diameter.	Reduced Area. Sq. in.	Contraction of Area. Per cent.	Elongation in 2 ins. Per cent.	Load in lbs.	Breaking Strain. Lbs. per sq. in.
0·116	0·01057	0·106	0·0088	16·5	6·25	2,100	198,700

The high tensile strength of this wire, with the comparatively small reduction in elongation and contraction of area, indicates extreme toughness, and at the same time the material is not acted upon, or but very slightly, by salt water.

The *magnetic properties* of Nickel steel alloys show very marked peculiarities. Thus, steel containing 25 per cent. Nickel is scarcely magnetic at all until cooled to a temperature of − 40° C. After exposure to this low temperature, however, it remains magnetisable at ordinary temperatures, and does not recover its original condition until heated to 600° C.

It has been shown by Guillaume that Nickel steel alloys may be divided into two classes as regards their magnetic properties. The first or reversible class comprises those alloys which lose their magnetic properties on heating and recover them on cooling to the same temperature. The second or non-reversible class comprises those alloys which contain 25 per cent. or less of Nickel, and which have magnetic properties similar to those of the 25 per cent. alloy mentioned above.

It has been shown that an alloy with 35·7 per cent. Nickel, and containing Chromium, lost its magnetism at 210° C., whereas a similar alloy without Chromium retained its magnetic properties up to 235° C. Chromium, therefore, seems to have the effect of lowering the temperature of transformation.

The magnetic and electrical properties of iron-nickel alloys have been examined by C. F. Burgess and J. Aston * on a series of alloys in which the impurities have been kept down to the lowest possible point. The magnetic tests were made upon an Eaterline permeameter on the specimens containing from 0·27 to 75·06 per cent. Nickel in an unannealed state, and also after annealing at 675° C. and 1,000° C., and quenching at 900° C.

In the annealed state, up to 1·93 per cent. Nickel the magnetic properties are little inferior to electrolytic iron. Additions of Nickel cause a falling off in quality until at 22·11 per cent. they are very poor, and with 25·20 per

* *Metallurgical and Chemical Engineering*, vol. viii., No. 1, Jan. 1910, pp. 23-26.