A Thesis on the Process of Puddling Steel with the Codorus Ore.

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In this paper I propose to give some account (1st) of the history of steel puddling, (2nd) of the performance of the process and its chemistry, and (3rd) some statistics to show the value of puddled steel, its tensile strength etc.

In preparing this thesis I have referred copiously to various publications; all that refers to the Codorus process directly is from my own analyses, observations and experiments at the Norway Iron Works, in South Boston Mass.

I

The process of puddling iron consists essentially in exposing melted, highly carburized iron, on the open hearth of a reverberatory furnace, at a temperature at which it is readily fused, to the oxidizing action of the air, and of a rich bath of slag or cinder, with or without the introduction of fluxes: in stirring it with appropriate instruments (1st) to render it as nearly homogeneous as possible and (2nd) to expose it more thoroughly to the air; in keeping up this operation till the metal is so far decarburized as to be no longer fusible at the temperature of the furnace, when it solidifies as a sort of granular, waxy precipitate, which is collected into balls to be subsequently shingled into what are called "muck bars".

It is generally believed that it was first invented and patented by Henry Cort.[1] His claim seems to me to be

[1] Manufacture of Iron, 1784, no 1420

small, as far as priority is concerned, in spite of the elaborate paper published in his behalf[1]

It appears that the process of puddling had been patented twice before, first[2] in 1766 and (second)[3] in 1783, the first 18 years, the second one year prior to the date of Cort's patent.

In 1766 Messrs Thomas & George Cranage did actually produce balls of malleable iron, in a reverberatory furnace, from pig iron, using a method which differed in no essential feature from puddling. They did not persevere in

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1. "Statement of the Claims of the Surviving Members of the Family of the late Henry Cort for National Compensation"

2. June 17, 1766. no 851. "Making pig iron malleable in reverberatory or air furnace, with raw pit coal only"

3. May 7, 1783. no 1370 "A new Method of Working and Refining Cast or Pig Iron, and converting the same from a fluid state Wrought or Bar Iron, which would be of Publick Utility"

their process, nor bring it to the notice of the trade, so that little gratitude is due them.

Again in 1783, the year before Cort took out his patent, a patent was granted to Peter Onions, in the specification of which the process of puddling is most minutely and graphically decribed. The description is of such a nature as to leave no doubt that Onions had actually, and probably repeatedly, seen the process in operation.

Nor are the claims of these patentees on a par with those of a well known aspirant to the honor of having discovered a certain anaesthetic; for they had not only conceived and recorded their ideas, but had actually put them into practise, and, it is highly probable, on a commercial scale. That they should have continued to puddle iron is not in the least necessary to the establishment of their claims as inventors, as a thousand circumstances may have prevented them; such as the want of capital to build furnaces, or the unwillingness to engage extensively in a process whose products, (however thoroughly they might might be convinced of their virtues) were not yet tested and approved by the public.

Whether or not Cort was an inventor of puddling, i.e. whether he worked out for himself the process specified in his patent, without being indebted for any of his ideas, directly or indirectly to the processes of Granage and Onion or any other persons, must probably remain for ever undecided. That he was not the first inventor but the third seems to be incontestibly established. That we are indebted to Cort for

bringing the process to the attention of iron masters, and ~~of~~ successfully establishing its commercial value is almost as certain: so that, inventor or no, we are as much indebted to him as to either Cranage or Onions.

It seems strange that it did not occur to the inventors of puddling, and to the manufacturers who employed it, that at a certain point in the decarburizing process the % of carbon in the metal must be such as to produce steel instead of iron, and that, if the process could be stopped at that point regularly, steel could become a normal product of the operation. So little, however, were they given to a priori reasoning that it is not till 1824 that we find any definite suggestions on the subject.

In the "Annales des Mines" 1824, 9, p. 327 we find this passage: "I am convinced that with" (the darkest, lee plus noires)" such pig irons, it would be possible to produce cast steel on a very large scale in reverberatory furnaces, by following a process analogous to that of the depuration of bell metal, that is to say by adding to the metal in fusion a portion of the same metal oxidized; or, still better, natural oxide of iron." It was not till 1835, 11 years afterward, that this idea was put into practise; and it seems pretty clear that even then the plan came from a posteriori rather than a priori reasons.

For some reason or other; the furnace being so cold that the metal, when only partly decarburized, was already infusible; or the cinder being acid and not of an oxidizing tendency, or very fluid, so as to prevent the air from exerting it's full influence on the charge; or the flame too smoky, or whatever; from some cause or other, I say, the balls were ~~soon~~ steely. Having accidentally made steel by puddling, it would not require a very ingenious mind to infer that steel might be made as a normal puddled product.

In 1835 Messrs Schlegel, Müller & Mayer patented[1] a process for puddling steel, which, however, they did not seem to succeed in themselves. Several other iron masters attempted to puddle steel, at various times from 1840-1849. In 1849, 65 years after Cort made public the puddling of iron, it was shown for the first time that steel could be profitably produced on a commercial scale by puddling,[2] and from ~~time~~ that time puddled steel became an article of great commercial importance. The managers of several Westphalian iron works combined, made many experiments, and finally succeeded in producing puddled steel with a considerable degree of regularity and

[1] Jahrbuch 1853, 3, p. 281. Report on International exhibition of 1851 p 181

[2] Annales des Mines 1859, 5, p 296

uniformity.

In 1850 Messrs Lehrkind, Falkenroth & Co., of Haspe, erected several puddling furnaces for the production of steel, and supplied the continental markets with puddled steel of various degrees of hardness; most of it was high steel, the application of mild steel to the arts not having yet received much notice. It was sold at $55.00 per ton, which seems a very modest price for steel, when we reflect that puddled iron is now sold wholesale at $85 @ $95 per ton.

Though the production of puddled steel in Germany and France was of such commercial importance, it was not introduced into England till about 1856; it was first made there at the Mersey Steel and Iron Works. From this time the manufacture rapidly increased.

It was noticed, a few years ago, at a Pennsylvania iron works, that when the puddling furnaces were "fettled" with the

Codorus ore, the product was steely; this happening frequently, it occurred to the manufacturers that steel might be made as a normal product of the process; the conditions necessary to the formation of steel were determined by trial, and the experimenters were so successful as to feel warranted in presenting the process to the notice of iron masters generally.

It was at first imagined that the ore had mysterious qualities, by which it "refined and purified the iron": perhaps likening it to the "steel-like nature of the Dannemora ores" mentioned, apparently in good earnest, by a certain French metallurgist of note. It was thought that it would much improve the products of any process of manufacturing iron. Messrs Naylor Vickers & Co caused some of the ore to be placed in a Bessemer converter at the beginning of a blow. Three blows were made, the circumstances being as nearly alike as possible all, with the exception that in one blow some Codorus ore was charged, while in the other two it was not.

The result was what might have been expected from the operation of the ore in the puddling furnace; the melted mass frothed violently and was thrown out of the vessel in large quantities. The other two blows were quiet, with nothing particular to mark them. The ingots from the blow with the ore rolled miserably, falling to pieces, and being so redshort as to be worthless except as scrap. The ingots from the other blows rolled beautifully, more like copper, indeed, than iron; working without flaw or crack.

The results of this experiment were so disastrous that, as far as I know, no further attempts[1] have been made to apply the Codorus ore to the Bessemer process.

The process of puddling with the ore has met with varying success at different

[1] See page 11 1/2

[Since writing the above I have obtained from Adolph Schmidt, Ph. D., of the Bessemer Steel Works, Troy, N. Y., the following particulars. "The Codorus gentlemen claimed that by the introduction of a certain o/o of their ore into the Bessemer cupola, with ordinary American anthracite pig, a complete elimination of P and S would follow in the course of the fusion preparatory to running into the converter" — "On Feb 22d the cupola was charged with 7,100 pounds of No 1 Hudson pig, which contains:

Silicon	3.974 o/o
Sulphur	0.139 o/o
Phosphorus	0.178 o/o

and 12.6 o/o Codorus ore. A rather longer time was allowed for the fusion than ordinarily given. There was tapped into the converter 6,700 lbs, the blow lasted 16 minutes, when 400 lbs spiegeleisen was introduced. The only difference noted was that the

charge was rather hot, which was to be expected from the high percentage of silicon." — "The fracture proved most conclusively the presence of phosphorus. [It is true that a cold chisel was made, but a soft steel suitable for rails was not made." — "An ingot was sent to the Rensselaer mill to be rolled into rail. After two passes the rolling had to be abandoned, thus proving the total unfitness of this steel for rails."

Several other blows were made with and without the ore, with Hudson pig, which showed beyond a doubt that the ore does not remove phosphorus, but that it is very prejudicial to the Bessemer process, as it causes gobbing and scaffolding in the cupolas.]

works. At the Bay State Iron Works, So. Boston, for example, though the patentees had the operation carried on under their immediate direction, it was a complete failure: the product, though indeed steel, was of a very inferior description. I think this failure may ascribed, at least partially, to the large size of the puddling furnaces, which, as I shall try to show beyond, is, and must be, fatal to the process, from the fact that it will is impossible to regulate the heat with the desirable nicety.

At the Norway Iron Works, on the other hand, it has met with quite a tolerable success, though not as brilliant a one as had been hoped for. It has been adopted there extensively; one turn (10 hours) of all the puddling furnaces being devoted exclusively to it. Steel, for purposes where hardness without great tensile strength is needed, such as wagon tires, sleigh shoes, toe calks, etc. etc., has been and is still manufactured for the market with a constantly increasing demand. In some cases it is combined with Norway or Swedes iron to give it the desired toughness; as, for instance, in the case of toe calks, when the outside of the toe calk is of pretty hard Codorus steel (carbon 0.92), the inside being of Norway iron (carbon 0.32). In the manufacture of better grades of steel, such as spring steel, they have not been so successfull. Though several lots of spring steel, of various sizes, have been taken by different parties, one only, and that a small lot, has given entire satisfaction: this lot was used for volute springs for railway cars. I shall show beyond why the higher grades of steel cannot be made by this process as well as the lower grades

The steel is tough, hot and cold, when thoroughly annealed. It hardens well, being when properly tempered very elastic, and has all the ordinary characteristics of steel.

Again, at the Albany Iron Works, So. Troy, N.Y., a few heats of puddled steel were made by the Codorus process, under the superintendance and at the expense of the proprietors of the process. I am informed by the superintendant and the boss puddler of that works that the steel made was of good quality, that it rolled well and was very juicy (from the fluidity of the cinder); that its grain was closer that that of ordinary puddled steel.

They also said that though the steel was undoubtedly much better than if the ore had not been used, yet it was no better than could be made with the "physic" which had been ordinarily used at their works, and the expense of making it would be greater.

Some of the steel puddled at the Albany Iron Works was taken to the

Rensselaer Iron Works, and there rolled into rails. Mr Babcock, the superintendant, informs me that the steel was of very good quality, and rolled very well; he is however of opinion that it cannot be made as cheaply as Bessemer steel, and that it is not so well fitted for rails.

II.

When the puddling of steel was begun at Haspe in 1850, it was probably made by what is known as Riepe's process[1]; so called from the fact that it was patented in England in the name of Ewald Riepe, though it does not appear at all certain that he was the inventor of it.

His specification is as follows. "Firstly. I employ the puddling furnace in the same way as for making wrought iron. I introduce a charge of about 280 lbs. of pig-iron, and raise the temperature to redness. As soon as the metal begins to fuse and trickle down in a fluid state," (it would be rather difficult for it to trickle unless it were in a fluid state) "the damper is to be partially closed, in order to temper the heat. From 12 to 16 shovelfuls of iron cinder discharged from the rolls or

[1] Improvements in the Manufacture of Steel. Jan. 29, 1850. No. 12950.

squeezing machine are added, and the whole is to be uniformly melted down. The mass is then to be puddled with the addition of a little black oxide of manganese, common salt, and dry clay, previously ground together.

After this mixture has acted for some minutes, the damper is to be fully opened, when about 40 lbs. of pig-iron are to be put into the furnace, near the fire bridge, upon elevated beds of cinder prepared for that purpose.

When this pig-iron begins to trickle down, and the mass on the bottom of the furnace begins to boil and throw out from the surface the well-known blue jets of flame, the said pig-iron is raised into the boiling mass and the whole is then well mixed together. The mass soon begins to swell up, and the small grains begin to form in it and break through the melted cinder on the surface. As soon as these grains appear, the damper is to be three quarters shut, and the process closely inspected, while the mass is being puddled to and fro beneath the covering layer of cinder.

During the whole of this process the heat should not be raised above cherry redness "(sic)" or the welding heat of shear steel. The blue jets of flame gradually disappear, while the formation of grains continues, which grains very soon begin to fuse together, so that the mass becomes waxy, and has the above-mentioned cherry redness.

If these precautions are not observed the mass would pass more or less into iron, and no uniform steel product could be ~~produced~~ obtained.

As soon as the mass is finished so far, the fire is stirred to keep the necessary heat for the succeeding operation, the damper is to be entirely shut, and part of the mass is collected into a ball, the remainder being always covered with cinder slack. This ball is brought under the hammer and then worked into bars. The same process is continued until the whole is worked into bars.

When I use pig iron made from sparry iron ore, or mixtures of it with other pig iron, I add only about 20 lbs of the former pig iron at the later period of the process, instead of about 40 lbs.

When I employ Welsh or pig iron of that description, I throw 10 lbs of best plastic clay, in a dry granulated state, before the beginning of the process, on the bottom of the furnace. I add, at the later period of the process, about 40 lbs of pig iron as before decribed, but strew over it clay in the same proportion as just mentioned." etc. etc.

The reason for adding less pig at

the second part of the process if spathic pigs are used than otherwise is probably this. The only object of adding the 2nd charge of pig is to give increased fluidity to the charge. But if a spathic pig is used, from the high percentage of manganese they contain, a smaller addition will suffice to give the required fluidity.

This method differs from the Codorus process in several particulars of more or less importance, though the essence of the two processes is the same.

I give here a description of the Codorus process as I have seen it carried out by Mr Hersey, a puddler of great intelligence and experience at the Norway Iron Works.

On Monday, July 10th, 1871, 301 lbs of No 3 Glendon pig were charged with 65 lbs of Codorus ore at 1.30 P.M.

N.B. The time given is from the time of charging.

Everything closed, a smoky flame pressing gently out of the doors.

12 min. The pigs are turned so as to expose new surfaces to the heat. The furnace is cold, not above a cherry red. Full blast is on

15 min. Fire is stirred

20 min. Pigs turned; the heat has now reached a full yellow.

23 min. Coal charged.

30 min. The notch is now uncovered. The iron is a good deal melted, and is now stirred about with the rabble. The heat is now nearly white.

34 min. Fire stirred from behind. Flame clear yellow. Damper is up. Puddling begins now

37 min. Entirely melted. Stirring vigorously

42 min. Flame somewhat smokier. cinder very thin.

45 min. The helper, who has done the stirring till now, is relieved by the puddler.

46. min. The boiling begins, though now very gentle, and the cinder is still thin.

51. min. The damper is raised a little. The most rapid decarburization now begins

54 min. Coal charged

59 min. Bath beginning to become frothy, and to rise: damper closed a little and kept somewhat smoky.

61. Puddler is relieved by helper.

65. Bath is rising rapidly, becoming very frothy; cinder somewhat thicker. Metal begins to show signs of coming to nature. Boiling violently.

70. Metal has pretty much come to nature; flame smoky, furnace cooler. Bath thick and pasty.

The metal is now nearly as fully decarburized as it will be. It is rapidly solidifying or precipitating. The damper is now lowered to prevent it from losing too much carbon, or becoming burnt.

? [illegible] 2.50 min. it has now completely come to nature & is being collected into balls.

? 2.53. The first ball is taken to be shingled

? 2.59. The third and last ball is taken to be shingled.

These balls were hammered, and twice reheated and rehammered, then rolled at one heat into 1⅛ in. square rods for steel wire. They rolled very well showing no flaws. Their fracture was crystalline, and showed specks of cinder here and there; but for the cinder they would be pronounced to be a superior article.

The size of furnace employed for Riepe's process was apparently about the same as that at the Norway Iron Works, which is designed for a charge of 300 lbs. The object of having such a small furnace, or rather, as Bauerman says, such a small bed in comparison with the grate, is to have full control over the heat; this is of the highest importance in steel puddling, perhaps as much so as in any metallurgical operation.

I cannot agree with Bauerman's statement that the small size of the bed is "in order to be able to command a very high temperature", as it seems to me calculated to mislead. According to Riepe's statement the highest heat needed is a cherry red; now although this was afterward explained, to by some quibble, to mean not a cherry red, but a much higher heat; yet, as far as I can learn, no one has ever used a very great heat in steel puddling. The use of the highest heat attainable in the puddling furnace, claimed by a subsequent patentee, seems indeed to accord with Bauermann's idea. But this claim seems to me to show a want of practical knowledge of the matter. The temperature need never be so high in steel puddling as, for instance, at the balling period in iron puddling, when a high welding heat is barely enough.

Still, he is perfectly right in excepting to Riepe's direction that "during the whole of this process the heat should not be raised above cherry redness". Now Cherry redness is generally understood to mean the heat intermediate between a dark red, which is the lowest heat at which iron is luminous by daylight, and a bright red or light cherry red. If the furnace were never raised above this heat the pig iron could suffer little decarburization before reaching the point at which it would be no longer fusible, but would solidify or "come to nature". By this means only the highest hardest steels could be produced; yet Mr Clay, in his paper of Jan 20, 1858, stated that he had made steel by this process which he believed would be "useful in the arts for all purposes for which steel is required, <u>except</u>, perhaps, for the finer descriptions of <u>tools</u> and <u>cutlery</u>". But these are the very classes of steel which require a high % of carbon. Here is evidently a contradiction, and the easiest way out of it is perhaps to allow that Riepe meant by cherry red a very bright red or by a little stretch a dark orange heat, as this would suffice for most of the qualities grades of steel then in demand, mild steel not having been brought to general notice, as I have remarked before.

They have built at the Norway Iron Works some new furnaces for steel puddling, of 400 lbs capacity, the increase of size being due mainly to the greater depth of the bed, the other dimensions remaining about the same as in the 300 lbs furnaces. The largest charge so far in these furnaces has been 300 lbs, but they intend to charge them to their full capacity. I apprehend that they will not work so well with so heavy a charge, as it will then be less easy to regulate the heat with the ~~required~~ requisite nicety.

In Riepes process the pig is charged in two portions, the second being introduced when the first is already well melted. I doubt if much is gained by this, except delay and trouble. Introducing 40 lbs of highly carbonized iron into the already partially decarburized bath has merely the effect of putting the process of decarburization back a few minutes: as the whole charge must again pass through exactly the same state as that which it was ~~wo~~ in when the second charge was introduced, and that too very soon, (as the influence of 40 lbs cannot put the whole mass back very much) it is hard to see what is gained. Should the bath accidentally become too far decarburized, the introduction of a little pig to bring it up might be very desirable.

This plan of charging a second portion of pig is directly opposed to the statement in Bauerman that "the use of only one kind or class of pig iron is also necessary, otherwise, supposing white and grey iron to be mixed, a ~~charge~~ portion of the charge would probably fine and come to nature while the more fusible part was still uncharged." Most weak and impotent conclusion! Anyone who has witnessed the process of puddling, and knows how thoroughly the charge is mixed with the rabble, indeed a condition, _sine quâ non_, will have no little difficulty in conceiving the state of affairs which Bauerman dreads.

The introduction of mill cinder and Schafhäutl's patent powder¹ or its equivalent has a most important bearing on the whole process. The part which this mixture plays is very nearly that of the Codorus ore. In the one case we have mill cinder, (magnetic oxide of iron), which with silica from the fettling and the clay, and with silicon from the pig metal, forms the bulk of the cinder, a tribasic protosilicate (with perhaps some persalt) of iron; manganese; and silicate of alumina. The alumina is capable of playing a double

¹This powder was patented A.D. 1835 May 13, (No. 6837). It was used in the manufacture of malleable iron. It consisted of an intimate mixture of 1¾ lbs. of black oxide of manganese (MnO^2), pyrolusite, 3¾ lbs. of well-dried common salt and 10 ounces of well-washed potter's clay. This mixture is to be melted with 3¾ cwts of pig-iron in the boiling process of puddling; and it is recommended to add it in three successive portions

port, sometimes acting as acid, sometimes as base, so keeping the equilibrium. It is moreover useful in promoting fusibility, when present in small quantity, by giving a mixed character to the cinder.

In the other case we have nearly the same components. I found 100 parts of the ore to consist of

Protoxide of iron	2.14		
Peroxide of iron	44.87	Protoxide of iron	0.63
Protoxide of manganese	0.71	Alumina	4.31
Magnesia	0.09	Magnesia	0.04
Lime	0.26	Lime	0.17
Potash	2.69	Potash	1.54
Siliceous matter	47.91	Silicic acid	41.22
Organic matter	0.80	Siliceous matter	47.89
Copper	0.00		
Titanic acid	trace		
Phosphoric acid	trace		
Sulphur	trace		
	100.33		

Of these the only constituents present in sufficient quantity to affect the

process are	Potash	4.23
	Oxides of iron	47.64
	Silicic acid	41.22
	Alumina	4.31
		97.42

In both cases we have silicate of iron, alumina and alkali in the cinder; in Riepe's process we have moreover both Mn & Cl.

The silicate of iron, as before observed, forms the bulk of the cinder, and much depends upon the proportion which its acid bears to its base; if the cinder be too acid it solidifies too soon after leaving the furnace, and it is then impossible to squeeze it out by hammering or rolling; the consequence is that the iron is full of cinder and works badly. If, on the other hand, the slag be too basic it will decarburize the iron too rapidly.

The presence of Manganese in Riepe's

process is of almost incalculable advantage, as it not only makes the cinder as fluid as the oxide of iron does, more so indeed, but does not decarburize the bath. In addition it oxidizes the sulphur of the pig metal, and is the best preventative of redshortness.

To make up for the absence of Manganese from the ore, in the Codorus process, Mr Gogin, the superintendant of the Norway Iron Works, will probably add a small amount of Spiegeleisen during some part of the process.

This I think will probably obviate the most serious defect in the Codorus process, viz the fact that much cinder remains in the steel which cannot be removed by any mechanical contrivance which they have yet tried. This cinder swells up and causes blisters on the steel, thus not only weakening it, but injuring its appearance.

These blisters seem to be of quite a different character from ~~fr~~ that of the blisters on steel of cementation. The latter usually disappear on rolling; the former will not. Moreover, certain sizes of ~~blister~~ Codorus steel blister much more readily than others. I have not been able to verify this latter statement by my own observations, but I am informed by Mr Geo. Gogin, of the Norway Iron Works, (who has had ample opportunity to observe the working of the steel), that "bars 1/4 inch thick blister much more readily than those thicker or thinner; that a piece rolled from 1 inch square down to a thickness of 1/4 inch will blister much less than if rolled from 3/8 inch to 1/4 inch in thickness; that, moreover, the bars do not show the blisters till they have passed the finishing rolls." I am inclined to regard this statement with some incredulity.

To obviate this difficulty it has been proposed to hammer the balls, when first taken from the furnace, very gently, so as to leave them in a somewhat porous state; to then reheat them in a bath of cinder, instead of on a sand bottom. The reason for this step would be that if they were heated on a sand bottom, at a temperature high enough to keep the cinder fluid, the steel would be liable to be "burned." (In the present state of ignorance about the metallurgy of iron, the burning of steel and iron must be taken as a stubborn fact, not yet accounted for. The weight of evidence seems to point out that the burning of iron is an oxidation, not merely on the outside, but extending far into the metal.) If, however, the bloom were protected by a varnish of cinder,

there would be no danger of this.
A serious objection to this plan occurs to me: the bloom lying in this bath of cinder, though not liable to become "burnt", will yet be rapidly and moreover irregularly decarbonized, from the oxidizing nature of the slag. This will not only render the nature of the product less certain than now, but also less homogeneous.

Two ways occur to me of surmounting this difficulty; either to render the cinder more fusible and less decarbonizing by introducing manganese, or to reheat the blooms in the reducing smoky flame of a gas furnace, or both. The slag at the Norway Iron Works is not only too infusible but too basic also. Though I am unable to support this statement by the results of analyses, yet I am confident that it is correct, from the appearance of the cinder. When cool it is covered with a very thin, bloom-like, red dust, of oxide of iron: were there not a deficiency of acid, I think that this could hardly occur. I have never seen it on other tap cinders. This was thought at the Norway Iron Works to be the phosphorus eliminated by the action of the Codorus ore, till I showed that it contained much less phosphorus than the rest of the cinder, by actual analysis.

It thus seems to me that the introduction of manganese is almost a necessity.

Let us now consider the other components of the ore and flux. In Riepe's method we have chlorine and soda, in the Codorus method we have potash. The effect of the chlorine does not seem clear. Tunner thinks that it causes many of the noxios ingredients of the pig iron to volatilize. This is no doubt very clever, but I don't know what it means. Whether chloride of phosphorus or phosphide of chlorine is volatilized he does not specify: he merely throws in a lot of impurities, from which "you pay your money and you take your choice." The probability is, as Percy says, that silicate of soda is formed, and chlorine is driven off. The chlorine is probably merely a vehicle to introduce the sodium into the slag; certain it is that none of the chlorine is found in the slag, while the soda is.

The alkali, soda in one case and potash in the other, serves one, and very likely two, very important ends. Soda, and, in a greater degree, potash render the slag very fluid. A little potash will leaven the whole cinder: though in the Codorus process the potash is only 0.7 o/o of the whole charge, I do not hesitate to say that it plays a more important part than any other ingredient of the ore.

A light fluid cinder is very much needed in steel puddling. In order that the process may be stopped at any particular point of decarburization with any degree of certainty, it is necessary that it should proceed slowly. This slow rate of decarburization will be effected (first) by a moderate temperature and smoky flame, (secondly) by having a cinder not too oxidizing, i.e. not too basic, and (thirdly) by having the metal well protected from the atmosphere by a fluid cinder.

Again, the more fluid is the cinder the more effectually can it be squeezed out of the ball, as has been already pointed out.

The second of the two important ends above referred to is shrouded in mystery. Tunner[1] thinks that in Riepe's method the soda contributes essentially to the formation of cyanogen "whereby the formation of steel, by means of cementation, especially after

[1] Jahrbuch 1853, 3, p 291

the termination of the rabbling period, is greatly promoted"

There seems to be a conviction in the minds of the best metallurgists that the cyanogen compounds play an important part in the manufacture of steel. Tunner observes that the nostrums of steel puddlers consist generally of cyanogen compounds, "or of nitrogenous matters capable of yielding cyanogen at high temperatures" such as sugar, leather, horns, hoofs, sal ammoniac, salt & vinegar, urine, silk waste, wood charcoal etc. etc. Cyanogen, like silicon, titanium, chromium, tungsten etc, has the power of replacing carbon in steel, and of giving the metal the same essential qualities, with certain very slight modifications. Whether the cyanogen compounds in any particular process furnish cyanogen to the steel, or merely act as vehicles to transfer carbon (and perhaps nitrogen) to the steel can be better told from the results of analyses than from a priori grounds. Again, whether the potash in the Codorus process and the soda in Riepe's process actually do assist by the formation of cyanogen or not is a ~~question~~ point to be proved, not assumed.

When the second charge of pig iron has melted, in Riepe's method, and has been raked down into the bath, affairs are in about the same state as when, in the Codorus process, the metal has been melted about ten minutes. Up to this point the heat in the Codorus process has averaged a fair yellow, while in Riepe's method it has been much lower. The rest of the operation is much alike in the two processes; in principle, identical. The time occupied in the Codorus is much less than in Riepe's process, as might be reasonably expected from the much greater heat employed in the former. I give on the next page a table by which the times of each period of the two processes can be compared with each other, and with the times of the corresponding periods in iron puddling;

Periods	Iron	Riepe's process	Codorus process
Melting	30–40 minutes	40–50 minutes	35 min
Stirring	30–35 "	45–50 "	25 "
Boiling	25–30 "	20–25 "	20 "
Balling	10 "	10 "	9 "
	85–115 "	105–135 "	89 "

The time given as occupied by the Codorus process is probably a little shorter than the average, as the steel produced was very high, the furnace being a shade too cold; the steel was intended for wire rods, and had of carbon 1.10. The workmen usually finish five heats per turn, and this they do in about nine hours, which gives 110 minutes for each heat; subtracting from this 10 minutes for repairing furnace between heats and we get for each heat 100 min.

$$\begin{array}{r} 60 \\ 9 \\ 5\,\overline{)540} \\ 110 \text{ about} \\ \underline{10} \\ 100 \end{array}$$

About 80 minutes are occupied at the Norway Iron Works per heat in iron puddling.

100 minutes is a very decidedly smaller period than that occupied by Riepe's method, and about a mean between that and the time occupied in iron puddling.

The statement in Bauerman that "At Lohe, in Siegen, twelve heats of 3½ cwt of white fibrous "steel" pig iron are puddled in the turn of twelve hours" seems almost incredible. It is not very probable in the first place that workmen could be got to work twelve hours; eleven hours is a long day's work for puddlers. But allowing twelve hours, at least one hour would be needed at the end of the day for fixing the bed of the furnace; this gives 55 minutes per heat, subtracting from which ten minutes for repairing between heats we get 45 minutes for the length of a heat. This is only 45 o/o of the time occupied by the Codorus process and only 39 o/o of the time occupied by Riepe's process. Had he said "twelve heats in two turns of twelve hours each" he would have allowed 100 minutes per heat, which, though a rather short allowance, is not an improbable length.

$$\begin{array}{r} 11 \\ 2 \\ \hline 22 \\ 60 \\ \hline 12)1320 \\ 110 \\ 10 \\ \hline 100 \end{array} \qquad \begin{array}{r} 60 \\ 11 \\ \hline 12)660 \\ 55.55 \\ 10 \\ \hline 45 \end{array}$$

Having determined the proper proportions of the charge, (which can only be done by actual experiment) the most important point is the management of the character and intensity of the flame. Should a high steel be desired, it is evident that two things should be borne in mind. First, in order to cause the steel to come to nature, i.e. to solidify, the temperature must be so far lowered that the steel at the particular point of decarburization desired (or rather at a somewhat higher point, since the metal is always and unavoidably slightly decarburized in the after processes of balling, shingling, reheating and rolling) shall be infusible: should the heat be raised too high we shall get a milder steel; if kept too low, a higher steel.

Secondly, the cinder must be more fusible for a high steel than for a low one, and more fusible for a mild steel than for wrought iron, in order that the cinder may be forced out at the lower temperature at which it must be shingled and rolled. [This is the reason, referred to on page 13, why higher grades of steel cannot be so well made by this process as the lower grades, until some method of eliminating the cinder from the steel shall be invented, much more efficacious than the present method.] Should a mild steel be desired, the above conditions must be reversed of course

Again, the character of the flame should be closely watched; should it become too sharp and cutting (i.e. oxidizing) the steel will be too rapidly decarburized; the character of the cinder will also be materially affected by that of the flame.

Again, at the period of coming to nature the flame must be carefully watched. As soon as the steel begins to fall, or precipitate, in waxy, rice like grains, the damper must be closed, the grains collected as rapidly as possible, and the balls most carefully protected from the atmosphere; in a word, all the circumstances must be as reducing as possible, as at this time the metal is especially liable to become burnt and redshort, the sponge like state offering an immense extent of surface. At the same time the heat must be as strong as is consistent with the fusibility of the particular grade of steel which is being made, in order that the cinder may be as fully squeezed out as possible in shingling.

From these considerations, especially from the difficulty of getting up a strong heat __without__ an oxidizing flame in ordinary puddling furnaces, to say nothing of the considerations of economy, it seems to me that the Siemen's furnace would be a most invaluable concomitant of the Codorus process, as well as of steel puddling in general: or if not a Siemens furnace at least some form of gas furnace might be used.

It was claimed by the proprietors of the Codorus process that by it the phosphorus of the pig iron was eliminated. Were this a fact, the value of the process would be greatly enhanced. I cannot perhaps give a better idea of the deleterious effects of phosphorus on steel than by quoting the following passage from Knut Styffe's "Iron and Steel." In regard to this passage Percy says "The author pronounces a decided opinion on the injurious influence of phosphorus on Steel, and few men in Europe are entitled, from long and accurate observation to speak with greater authority on the subject."

Mr Styffe says "From the behaviour of iron rich in phosphorus, as recorded in the experiments above, it appears that phosphorus, like carbon, raises the limit of elasticity and strength <u>within</u> the crystalline particles of the iron (whence results the superior hardness of iron containing phosphorus); but that it does not increase the cohesion <u>between</u> the ~~particles~~ separate crystals.

Phosphorus, as is well known, renders iron more fusible, and increases its tendency to crystallize when heated. If, therefore, an iron rich in phosphorus has assumed a coarsely-crystalline texture by exposure to a strong heat, and has not afterwards been stretched sufficiently to bring the component crystals close together, and elongate them so as to develope fibre, such an iron may prove hard on wear, although neither extensile nor strong when stretched. For it is principally the cohesion between the crystals in the iron that is of importance, and not that between the particles within the individual crystals. The fracture of such an iron becomes, therefore, coarsely crystalline.

With reference to the Cleveland and Dudley irons, the unexpected tenacity of these bars, containing, as they did, so large an amount of phosphorus, doubtless resulted from the extension which they have suffered by rolling after the last reheating; and the development of a fibrous structure has probably been facilitated to a considerable extent by the intermixture of slag. In the sample of Cleveland iron (No. 12, Table IV.) the proportion of this slag amounted to 2.25 o/o, and in another bar (No. 10, Table IV.) to 3 o/o, whilst in the Dudley iron it was also 3 o/o; but the latter, judging both from its appearance and from its behaviour on forging, generally contained more slag than the former. The slag apparently has a tendency to oppose the aggregation of the crystalline particles of an iron rich in phosphorus, and hence it is that the irons previously mentioned have not been found cold-short even after exposure to a white heat. Other examples might be cited in which one substance when associated with another, although not in chemical combination, diminishes its tendency to crystallize. By extending the crystals so as to form fibre, the limit of elasticity is also lowered.

In an iron rich in phosphorus the intermixture of slag ought therefore to be beneficial, inasmuch as it is considerably diminishes its tendency to become cold-short; but it is well known that the cinder makes the iron unsound, and renders it incapable of being worked without cracking. Of the different brands of English iron examined, only that from Low Moor was fit for smiths' work.

An iron that is cold-short, but free from slag, such as the Ary iron, may be, (when heated), readily stubbed, flattened, or re-formed in any other way, without cracking; but it is of course not suited for use where a high degree of tenacity is required.

With regard to the influence of phosphorus on steel, our knowledge is at present more imperfect than it is with regard to the effect of that element on iron. It is, however, generally assumed — and apparently with good reason — that the presence of phosphorus is more prejudicial in steel than in iron, and that the more phosphorus the steel contains the more readily does it lose its characteristic properties by repeated reheating, so that at length it becomes impossible to temper such steel. The French chemist Caron, distinguished for his experiments on steel, explains this effect by supposing that the phosphorus, like silicon and sulphur, separates the carbon from its chemical combination with the iron. It is, however, known that those descriptions of steel which are most conspicuous for their power of enduring several successive reheatings without perceptible alteration — such as the steel manufactured from Dannemora iron — are precisely those which contain the least amount of phosphorus; and the author knows no authenticated instance in which the proportion of phosphorus has been higher than 0.04% in what has been considered a good steel"

[The italics are mine]. Few pig irons are to be bought at reasonable prices which contain less than 0.25 o/o phosphorus: from the above quotation it seems that o/o 0.04 is the maximum phosphorus for good steel. If the Codorus process can cause the phosphorus to diminish from 0.25 to 0.04 o/o many and cheaper pig irons could be used than can be for the Bessemer or Siemens Martin process, or than could be used for the Codorus process were it not for the eliminating power.

Principally with a view to settling this question I have been engaged by Messrs Naylor and Co, at Norway Iron Works, during the last four months, (June, July, August and September, 1871) on a series of analyses of the pig metal charged, of samples of metal and cinder taken from the bath at various stages of the process, and of the steel bars, the product of the Codorus process. The results of these analyses leave little doubt that the o/o of phosphorus does rapidly decrease during the process. The conclusions to be deduced from them would be much more satisfactory had a pig iron richer in phosphorus been employed. The phosphorus eliminated is not more than what we might expect would be eliminated by Riepe's process, judging from the results of Schilling's analyses. Nor does the analysis of the ore [p. 30] afford any reason to expect a greater decrease of phosphorus than in ordinary steel puddling. Still the results indicate that very probably pig iron of 0.2-0.25 o/o phosphorus might be puddled by this process so as to yield good steel.

I have also made a similar series of analyses with a view to determining whether sulphur was eliminated by the process: here again the same trouble arises as in the analyses for phosphorus, only in a much greater degree; the amount of sulphur in the pig iron is so very insignificant that no satisfactory deductions can be made from the results. What has been said in regard to the analyses of the metal is true of those of the several samples of cinder. These results serve as very good checks on each other, the o/o of the impurity increasing about as fast in the cinder as it decreases in the metal. It does not follow, though, that because we find a result a few hundredths of 1 o/o different from what we should expect from the results on either side of it, that either the result is wrong, or that there is any anomaly in the process; as, in a mass whose composition is changing so rapidly, and, moreover, whose fluidity is, at some stages, so imperfect, perfect homogeneousness is unattainable.

I give below the results of Schillings analyses, which seem on the whole more presentable than Le an's or than Calvert & Johnson's, my own results, and some others from various sources.

Results of analyses of iron and slag taken at different stages of puddling steel, at Zorge in Hanover (Schilling)

	1	2	3	4	5	6	7	8	9	10
Graphitic carbon	0.08	2.13	1.11	—	—	—		—	—	—
Combined "	2.60	1.03	1.81	2.49	2.36	2.26	1.77	1.33	1.08	0.94
Sulphur	0.09	0.109	0.10	0.03	0.027	0.012	trace throughout			
Phosphorus	0.48	0.46	0.47	0.24	0.17	0.11	0.08	0.071	0.075	0.075
Silicon	0.99	1.50	1.24	0.34	0.16	0.11	0.11	0.11	0.11	0.11
Manganese	2.01	1.13	1.66	0.47	0.47	0.47	0.31	0.31	0.27	0.27

No 1. White pig from Gittelde
" 2. Grey pig from Zorge
" 3 Mean composition of charge
" 4 Charge after melting down 47½ min after charging.
" 5. Metal at commencement of rising 18½ min after no 4
" 6. " at boiling 14 min later than no 5
" 7. " " " 17 " " " " 6
" 8. Granules beginning to separate, 14 ¾ min later
" 9. Sample taken at formation of first ball, 9 min later
" 10. " " " " " last " 9 " "

Corresponding Composition of Slags

Slags taken with	4	5	6	7	8	9	10
Silica	20.98	20.51	20.12	20.34	20.27	20.40	20.52
Phosphoric acid	5.25	5.25	5.25	5.25	5.25	5.25	5.25
Peroxide of iron	7.12	4.09	4.12	5.20	5.20	4.95	6.24
Protoxide of iron	58.98	62.03	62.14	61.20	61.20	61.34	59.88
Alumina	2.78	2.82	2.87	2.87	2.91	3.05	2.86
Protoxide of manganese	1.64	1.64	1.64	1.64	1.64	1.64	1.64
Lime	1.84	2.14	2.04	1.69	2.12	1.72	1.69
Magnesia	1.62	1.51	1.63	1.52	2.04	1.81	1.79
Alkalies	0.93	0.82	assumed at 0.87				
Sulphuric acid	trace	trace	not determined				
	101.14	100.81	100.68	100.58	101.50	101.03	100.74

"The metal of sample No. 3 was tough and strong cast iron; No. 4, taken after five mins had been heated in rabbling, was stronger than the preceding but of a tin white color; No. 5 was very cellular, and resembled white pig iron, but was slightly malleable; No. VI was decidedly malleable, and apparently possessed most of the properties of steel, notwithstanding the large amount of carbon present"

Results of analyses of iron and slag taken at different stages of puddling steel by the codorus process, at Norway Iron Works, So Boston Mass (H. M. Howe)

	1	2	3	4	5	6
Combined carbon	graphite 3.36 combined 0.22 total carbon 3.58	3.40	3.25	—	1.10	1.10
Phosphorus	0.16	0.05	0.036	0.03	0.03	0.02
Sulphur	0.004	0.005	0.02	0.007	—	0.002

No 1. Glendon pig iron, No 2
No 2. sample taken 42 min after charge
No 3. " " 57 " " "
No 4. " " 71 " " "
No 5. " " 100 " " "
No 6. Steel bar, product of the operation.

Corresponding analyses of Cinder

Cinder taken with	No 2	No 3	No 4	ten min before No 5	No 5
Phosphoric acid	2.48	4.91	4.91	5.49	5.20
Sulphur	0.15	0.26	0.24	0.23	0.28
Phosphorus (corresponding)	0.86	1.07	1.07	1.09	1.08

No 2 was taken from the bath a few minutes after the iron had become completely melted, before decarburization had set in. The carbon had passed from the graphitic to the combined state, as is shown by this fact: the pig metal, having little combined carbon, was quite malleable and soft, being readily drilled, and was moreover colored black by the crystalline plates of graphite; The sample taken from the furnace, being very rapidly cooled, especially on the outside, by the iron ladle in which it was removed, became a very hard chilled casting; i.e. the carbon (which at the moment of fusion was entirely combined with the iron, or "occluded" in it,) had not time to separate out from the state of combination; the effect was that as there was no graphite to color it, the iron was of a silvery white lustre; and, owing to the high o/o of combined carbon, it was impossible to drill, file or mill it. The edge of the hardest drill was instantly dulled by it. To render it possible to comminute it, the

sample was annealed by heating it to a strong heat and cooling it in lime. This produced little or no effect on it. It was then put in the midst of a hot charcoal fire, in a smith's forge, and allowed to cool in the fire over night. This softened it very much, much of the carbon passing from the combined to graphitic state, as was also shown by the darker color of the fracture. It should be noticed that the inside of the original fracture, before being annealed, was much darker and softer than the outside, both of these qualities showing that some of the carbon had had time to crystallize out as graphite, being farther from the cooling surface.
The % of combined carbon was determined from some chips obtained with great difficulty from the unannealed portion
No 3 was taken from the furnace during the

boiling period. The metal had barely begun to boil, and was not yet much decarburized; the sample had a silvery white fracture, showing that all the carbon was combined, and was quite hard, requiring a well hardened drill to touch it.

No 4 was removed toward the latter part of the boiling process, and was a granular sort of mass, which, owing to its peculiar structure, could not be drilled, but was broken up as thoroughly as possible in a mortar.

No 5 was taken while balling, and was much like No 4, like it being reduced in a mortar.

In regard to the analytical work I can only say that it was performed to the best of my ability; many results were duplicated, and all which I saw reason to suspect were rejected. Still it would be absurd to pretend to sufficient skill or experience to lay claim to any great degree of accuracy or reliance.

The determinations of phosphorus were all made by the "molybdate" method. The determinations of sulphur were made, in the case of the metallic samples, by a volumetric method, evolving the sulphur as sulphuretted hydrogen, and titrating the sulphide of sodium formed with iodine solution. These results were duplicated by the oxidation method, with chlorate of potash. In the case of the samples of cinder the sulphur was determined by oxidation fusion with alkaline nitrate and carbonate.

Note [I may here state the results of some experiments I have made to determine to what extent the sulphur of the coal gas was liable to contaminate the results of the last mentioned process

No 1. I used 3 grms nitre & 4 grms carb. soda in a platinum crucible enclosed in a porcelain crucible, several hours.

Barium chloride produced no precipitate in the aqueous extract.

No 2. Fused, Sept 19, 3 grms nitre and 4 grms carb. soda in a covered platinum crucible for seven hours. Chloride of barium produced in the aqueous extract of the residue 0.2158 grms of sulphate of barium; after purifying it with dilute HCl as directed in Fresenius it weighed 0.212 grms.

No 3. Fused, Sept 20, 3 grms nitre and 4 grms carb. soda, in an open platinum crucible for six hours. Chloride of barium produced in the aqueous extract a precipitate of 0.2564 grms of sulphate of barium, which, ~~as direct~~ after purifying weighed 0.2511 grms.]

Results of analyses of slag taken at different stages of puddling steel by Riepe's method

	1	2	3	4	5	6	7
Carbon	3.65	4.20	3.900	—	—	—	—
Silicon	1.13	2.06	1.658	—	—	—	—
Manganese	2.11	trace	1.055	mnO 2.38	mnO 1.36	mnO 3.00	mnO 2.00
Silicic acid	—	—	—	14.50	11.50	15.00	14.50
Iron (protoxide)	—	—	—	83.12	81.14	82.00	83.5

1. 80 kilog No 1 pig, from Alélik, Algiers
2. 120 kilog mottled pig, from Sollenzara, in Corsica
3. Mean of charge

Cinder.
4. sample taken during puddling, at end of second period, just beginning to bubble, 65 min after charge.
5. Sample taken 15 minutes later, before thickening. c
6. Sample taken 30 minutes later, when the boiling was at its height.
7. sample taken at tap

Results of analyses of No 1 pig, and puddled steel produced from it:

	Steel	Pig
Carbon	0.501	2.680
Silicon	0.106	2.212
Sulphur	0.002	0.125
Phosphorus	0.096	0.426
Manganese	0.144	1.230
Iron	99.151	93.327
	100.000	100.000

III

The figures which I give below show the much greater tensile strength of steel than of iron. That the mild grades of steel, which nearly approach wrought iron, will prove sufficient is not a matter of no doubt. Wrought iron will soon be a thing of the past. Although practiced for fifty years or for a thousand, but it [illegible] has already exhausted [illegible] the advantage of the mild steel over iron are obvious inasmuch as we have a mild steel twice the tensile strength of wrought iron, and costing but [illegible] as much, it is evidently not enough to use the steel as iron. [illegible] economy it is made much cheaper. In bridges for ordinary spans most of the strength of a bridge is required to sustain not the rolling load, but its own weight, and then we can use a material which has half the weight of wrought iron for the same strength, it is evident [illegible]

III

The figures which I give below show the much greater tensile strength of steel than of iron. That the milder grades of steel, which nearly approach wrought iron, will soon supplant it, admits of no doubt. Wrought iron will soon be a thing of the past, perhaps not ~~in~~ for fifty years, or for a hundred; but its glory has already departed. The advantages of the mild steels over iron are apparent; supposing we have a mild steel of twice the tensile strength of wrought iron, and costing twice as much; it is evidently as cheap to use the steel as the iron. For many purposes it is indeed much cheaper. In bridges, for instance; most of the strength of a bridge is required to sustain, not the rolling load, but its own weight; if then we can use a material which has half the weight of wrought iron for ~~the~~ a given strength, it is evident that we can use <u>much less</u> than half the quantity of material, which would be needed, were we to use the weaker substance.

When the "Commission of the Iron and Steel Institute on Mechanical Puddling" return their report, puddling may receive a new impetus: in fact the mechanical puddling furnace of Danks promises very well.

That puddled steel will ever be in much greater the demand than it now is I doubt very much. Its great and insuperable disadvantage is that it can never be homogeneous. Bessemer, Siemens-Martin and Cast steel "can be cast at once into perfectly sound and homogeneous ingots or masses of any desired size: whereas "puddled and bloomary iron and steel," being only an aggregation of the granules of metal which are developed, cannot be produced in large masses; but the comparatively small and imperfect blooms produced must afterward be welded together for forgings of even moderate size; a treatment, which even under the most favorable circumstances, and with the best skill and management, fails to give perfectly sound and homogeneous products

Another disadvantage, not so insuperable as the last, but still a very serious one, is the uncertainty inherent in the process of steel puddling. Here cast-steel and Siemens-Martin steel have it at a very great disadvantage; even the Bessemer process yields a far more certain and regular product than puddling does.

Still, as puddled steel can be made at present at a somewhat smaller price than the better grades of steel, at a price not much greater indeed than that of the best puddled irons, there will doubtless be some purposes to which it will be applied for perhaps many years to come. It seems to me very doubtful if its use will be accompanied by any real economy; as, if a good article is desired, a material which will resist a high tensile strain etc, it will probably always be the wiser policy to pay a little higher price for a more homogeneous and reliable steel, than to run the risk of an accident from the breakage of the steel, the results of which would probably incur an expense tenfold greater than that which would have arisen from using the better material.

If, on the other hand, the material is to be subjected to no strain, and strength is no object, it is not easy to imagine many cases in which puddled iron will not be as efficient as puddled steel. It is highly probable, moreover, that ere long Bessemer steel can be produced at as low a price as puddled steel: during the space of one year the production of Bessemer steel will be doubled, and, with the resulting competition, a decrease in the price may be confidently anticipated.

I append a table, showing the strength of wrought iron, steel and cast iron, for the purpose of showing how puddled steel in general compares with other materials. This table shows that puddled steel does not have the tensile strength of the stronger grades of Bessemer, cast and blistered steels, of homogeneous metal, or of wire iron, while it is much stronger than bar, plate and Bessemer irons, and, of course, than cast irons. Gun metal, also, is very much stronger than puddled steel.

The figures of this table I have collected from various sources, the works of Fairbairn especially having furnished me many valuable statistics.

I also give a table, by Christer P. Sandberg, which presents to the eye the properties of cast steel, & Bessemer & puddled material; it seems to me by far the most interesting, striking and instructive plate on the subject which has been presented to the engineering public. This plate shows that the various grades of Bessemer products have the same tensile strengths as the corresponding grades of puddled iron and steel and cast steel, from the hardest Uchatius steel to the softest Swedes iron, from metal of 1.22 o/o carbon to that of 0.06 o/o.

Tensile strength of Cast Steel

Description		lbs @ sq inch	Authority
Average		1342 56	Nystrom
"		886 57	Haswell
Maximum		1420 00	"
F. Krupp, Essen.	82549 @	854 31	Styffe
Uchatius steel from Wikmanshyttan No1		1388 86	"
" " " " "		1398 47	"
" " " " "		1447 19	"
" " " " "	No2, 117000 @	1213 88	"
" " " "	No3 103547 @	1186 43	"
Carlsdal " " "	65000 @	1399 16	"
Bar	100000 @	1300 00	Rankine
Forged	92000 @	1329 69	Napier
	~~78000 @~~	1300 00	Rennie
Plate	76000 @	962 89	Napier
"	85000 @	1029 00	Fairbairn
"		963 00	Haswell
"		800 00	Rankine
Razor steel		1500 00	Mosely
Soft "		1200 00	"

Tensile strength of puddled steel

Description		lbs @ sq inch	Authority
Hard, from Surahammar	84000 @	1053 31	Styffe
Medium, " "	74000 @	861 18	"
Soft	62000 @	798 67	"
Average	95000 @	1163 36	Barlow
"	121408 @	1738 17	Haswell
"	63000 @	714 84	Napier
"		90000	Fairbairn
		947 32	Mallet
Plate	71532 @	1052 93	Napier
"		936 00	Fairbairn

Tensile strength of Bessemer steel

Description		lbs @ sq inch	Authority
Forged		1114 60	Napier
Cast ingots		630 24	Wilmot
hammered		1529 12	"
Carlsdal "rolled	65000 @	1399 16	Styffe
Högbo tilted	98000 @	1273 64	"
Rolled		154000	Fairbairn
"		90000	Wilmot

Tensile strength of blistered steel

Description	lbs @ sq inch		Authority
Average	1331	52	Nystrom
"	1042	98	Napier
Minimum	1040	00	Haswell
Maximum	1330	00	"

Tensile strength of shear steel

Average	1184	68	Napier
"	1286	32	Nystrom

Tensile strength spring steel

Average	725	29	Napier

Resistance to Direct Crushing of Cast Iron

Description		lbs per Sq inch	Authority
Average	82000 @	1450 00	Rankine
No 1 cold blast	56000 @	805 61	"
No 1 " " Buffery		933 85	Fairbairn
No 1 hot "	72 000 @	887 41	Rankine
No 1 " " Buffery		863 97	Fairbairn
No 1 " " Coed Talon		827 39	"
No 1 " " Low Moor		624 50	Haswell
No 2 cold blast	69000 @	1624 08	Rankine
No 2 " " Carron		1063 75	Fairbairn
No 2 " " Coed Talon		817 70	"
No 2 Low Moor		923 30	Haswell
No 2 hot blast	83000 @	1020 30	Rankine
No 2 " " Carron	~~76900~~ "	1085 40	Fairbairn
No 3 cold "	76900 @	1134 00	Rankine
No 3 " " Devon		1454 35	Fairbairn
No 3 " " Carron		1134 42	"
No 3 hot "	102000 @	1048 81	Rankine
No 3 " " remelted		985 60	"
No 3 " " 12 times "		1637 44	"
No 3 " " 18 " "		1971 20	"
No 3 " " Carron		1334 40	Fairbairn
No 3 " Clyde		1060 39	Haswell
Stirling best		1344 00	"

Resistance to Direct Crushing of Gun Metal

Description		lbs per Sq inch	Authority
American best		1748 03	"
" mean		1290 00	"

Resistance to Direct Crushing of Wrought Iron

Description		lbs per Sq inch	Authority
Average		144 00	Hapstone
"	36000 @	400 00	Rankine
English best		652 00	Haswell
English	40000 @	652 00	"
American best		1277 20	"
" mean		835 00	"

Resistance to Direct Crushing of Cast Steel

Description		lbs per Sq inch	Authority
Average		2950 00	"

A Table

to

Accompany a Thesis on Puddling Steel

with the

Codorus Ore.

Strength of Bar Iron

Description of iron	Tensile strength in lbs to sq inch		Authority
Swedish	41000 @ 489	33	Napier
"	649	60	Telford
"	581	84	Franklin Inst
" best	720	00	Haswell
"	650	00	Nystrom
"	716	80	Rondelet
Russia	50000 @ 590	96	Napier
"	595	00	Haswell
"	394	70	Nystrom
"	604	80	Lamé
English	571	20	Lamé
"	560	00	Haswell
"	560	00	Nystrom
"	571	42	Lamé
Lancaster	586	61	Franklin Inst
~~Lancashire~~ Lanarkshire	51000 @ 601	10	Napier
Lancashire	34000 @ 647	45	"
Staffordshire	56715 @ 622	31	"
Low Moor	60000 @ 663	90	"
"	642	00	Fairbairn
Welsh	649	60	Telford
Tennessee	320	99	Franklin Inst
Missouri	479	09	" "
Phillipsburg	74000 @ 891	62	" "
Charcoal	636	00	Fairbairn
Extra	600	00	Rankine

Effect of rolling bar iron cold

Black bar	586	27	Fairbairn
The same turned	607	47	"
" " cold rolled	882	29	"

Tensile strength of plate iron

Description of iron	lbs	to sq inch		Authority
Average		510	00	Rankine
"		284	45	Fairbairn
Extra boiler		500	00	Rankine
American "		620	00	Haswell
English "		510	00	"
Yorkshire	52000@	584	87	Napier
"		510	04	Fairbairn
Staffordshire	46000@	569	96	Napier
" best best	50000@	598	20	Fairbairn
" " " charcoal		450	10	"
" "best"		612	80	"
" common		508	20	"
"		438	58	"
Lancashire		508	20	"
"	43000	538	40	Napier
Durham		512	45	"
Derbyshire		485	63	Fairbairn
Shropshire		511	31	"
Cold rolled		1149	12	"
Admiralty test, lengthwise, 1st class		492	80	
" " crosswise, "		403	20	
" " , lengthwise, 2nd class		448	00	
" " , crosswise, " "		380	80	

Tensile strength of puddled iron.

Surahammar	45000@	504	35	Styffe
Lowmoor	52700@	589	44	"
Middlesbro	53317@	725	31	"
Dudley	41738@	520	13	"
Cwm Avon	43642@	508	47	"
Motala	45632@	526	31	"
Puddled iron		439	04	Clay
The same five times repiled, heated & rolled		618	24	"
" " twelve " " " "		439	04	"

Tensile strength of wire iron

Description		lbs @ sq inch	Authority
Average		70000 @ 100000	Rankine
"		103000	Haswell
"	English	80214	Telford
Charcoal		100000	Rankine
"	very strong	114000	Morin
"	average	86000	Telford
"	weak	71000	Morin

Tensile strength of Bessemer Iron

Ingot	41242	Wilmot
Rolled	72643	"
Boiler	68319	"
Högbo tilted	68000 @ 71364	Styffe

Tensile strength of Homogeneous Metal

1st quality	96280	Napier
2nd "	72408	"
Average	100994	Barlow
"	90647	Napier
"	93000	Fairbairn
Forged	89724	Napier
Steely iron	69436	Barlow

Miscellaneous wrought irons

Rivet	63000 @ 81830	Fairbairn
Large forgings	44000 @ 47582	Napier
	33600	Morin
Yorkshire bridge iron	49930	Fairbairn
Staffordshire "	47600	"
Bushelled iron turnings	about 56000	Napier
Hammered scrap iron	53420	"
Angle iron	" 50000 @ 61260	"
Strap	41000 @ 55937	"
Best best loop	64000	Rankine
Sheet	40000	Nystrom
Äryd charcoal bloom	59864	Styffe
Hallstahammar charcoal bloom	50916	"
Lesjofors bloom made in Lancashire hearth	45000 @ 48720	"

Tensile strength of cast iron

Description		lbs to sq inch		Authority
Average	18000 @	450	00	Nystrom
	13400 @	290	00	Rankine
" American		318	29	Haswell
" English		194	84	"
Clyde No 1		161	25	"
Calder No 1		137	35	"
Cold blast No 1	13000 @	176	97	Rankine
Hot " No 1	13000 @	161	25	
Buffery No 1. Hot blast		134	34	Fairbairn
" No 1 cold "		174	66	"
Lowmoor No 2		140	76	Haswell
Cold blast No 2	13348 @	188	55	Rankine
Hot blast No 2	13505 @	178	07	
Carron No 2 hot blast		135	05	Fairbairn
" No 2 cold "		166	83	"
Coed Talon No 2 hot "		166	76	"
" " No 2 cold "		188	85	"
"Clyde" No 3		234	68	Haswell
No 3 cold blast	14200 @	135	08	Rankine
No 3 hot blast	15278 @	234	68	
Carron No 3 hot blast		177	55	Fairbairn
" No 3 cold "		142	00	"
Devon No 3 hot "		219	07	"
Stirling		257	64	Haswell
Greenwood		459	70	"
Malleable iron	about	480	00	Rankine

Tensile strength of gun metal

Average		372	32	Haswell
Coleford	10900 @	160	340	Fairbairn
Muskets		10 34	00	"