1922

High speed steel - its history, development, manufacture, metallography, and constitution, including an extended bibliography

James Presley Gill

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HIGH SPEED STEEL

Its history, development, manufacture, metallography, and constitution, including an extended bibliography.

A thesis submitted by J.P. Gill in part fulfillment for the degree of Master of Science in Metallurgy.

James Pressley Gill
Rolla, Mo. - 1922
There is no doubt but that the making of steel was known and practiced by the early Greeks probably several centuries before the birth of Christ. There have been discoveries of pre-historic forges and smelters evidently used for the making of iron and steel and it is certain that implements made of these materials dates back to antiquity.

As to the methods of making the steels of antiquity there is little known, but it is quite probable since iron has a strong affinity for carbon that in the forging of the iron it's contact with the carbonaceous fuel would absorb carbon with the result that this iron would prove harder than usual. The next step was probably the accidental discovery that this iron could be hardened by dipping in water. Such iron, or we call it steel, would undoubtedly make the superior tools of the time, but the art of metal cutting did not really begin until the age of machinery which dates back only about a century and quarter, and it is in this age that the real development of metal cutting began.

It is certain that high grade steels existed prior to the time of Christ. Such steels were represented by the Wootz Steels of India, the Damascus Steels made at Damascus, Syria, and the Toledo Steels made at Toledo in Spain. These steels were undoubtedly made by a crude crucible method, yet it seems that this method was entirely lost to civilization during the middle ages but was re-discovered by Huntsman in England about 1750, whereby we get the name Huntsman process applied to the present day crucible method of steel manufacture.

Proceeding the discovery of the crucible process by Huntsman, tool steels were made by the cementation process. This was done by heating iron inclose contact with charcoal or other carborizing material. This steel was made better when the muffle furnace came into use and the name blister steel was given it, due to the blister or scales appearing on it's surface during the process of carburization. It was known for a number of years that working this steel thoroughly improved it's quality, hence an improvement was made upon blister steel by breaking the blister bars into short lengths then bundling them together and welding. The sheer steel as this came to be called, was naturally of much better texture and uniformity. The same
process of breaking into small bar lengths, bundling and welding when applied to the shear steel further improved its quality and hence we get the name double shear steel. Shear or double shear steel was undoubtedly the best adapted steel for edged tools that had been produced up to this time.

It was about 1750 that a man by the name of Huntsman astonished his competitors by the uniform texture of his steel. It lacked the inequalities of carburization, seams, or streaks characteristic of the sheared steels. His method was soon discovered to be exceedingly simple. After carburizing the steel he broke it up into small pieces, melted it in the crucible and recast. This was the birth of the crucible process as it is known and practiced to-day and there is no process of steel manufacture that has existed as long as the Huntsman's process, keeping the essential features of the manufacture the same. This process has existed for nearly two hundred years and is only now giving way to the manufacture of fine steels by the electric furnace. Steel produced by the Huntsman's process was, of course, a simple carbon steel and tools made of this steel were perhaps far superior to any other steel of the time for cutting metals.

About the beginning of the 18th century, Mushet made a change in this process by adding the carbonaceous materials to soft iron and melting them down together instead of first making blister steel and remelting this blister steel as Huntsman did.

It did not seem to occur to any one to add alloys to the tool steel made by the crucible method until 1868 when Robert Mushet, The Second, found that one of his bars of steel had the property of becoming hard after heating without the usual quenching which had been used from time immemorial to harden steel. Such a singular experience caused an investigation of the bar and after an analysis was made it was found that the steel contained tungsten, thereupon Mushet began a system of experiments and investigations which eventually lead to the discovery of so-called Mushet Steel. This discovery really represents the beginning of High Speed Steel and undoubtedly ranks as one of the great discoveries in steel metallurgy.

A Steel by the name of "Robert Mushet's Special Steel" was soon marketed and found a large field of use. Shortly after this steel had come into general use Mr. Henry Gladwin at the Clyde Steel Works, Sheffield, noticed that one of the bars of Mushet Steel that had been laid at the door to cool was much harder than the bars that were laid farther back. Mr. Gladwin thought that this was due to the draught coming in through the door and thus started a series of experiments that lead to a far better heat
treatment of the steels of the Mushet type. Undoubtedly the discovery of tungsten steel was an accident, but a very fortunate one, and the same might be said of the discovery of the method of heat treatment given Mushet steel.

In 1894 Mr. F. W. Taylor in company with Mr. Haunsel White began experimenting with Mushet and other self-hardening steels that had recently come on the market with a view to determine which was best suited for special kinds of work. After a number of tests they decided that a certain make of steel was more efficient than others and could be run at a higher speed. They therefore decided to use this steel exclusively in the Bethlehem shops. In order to demonstrate the superiority of this steel and to have the co-operation of the shopmen, a number of tools were made from this steel and the shopmen were called to assemble to witness the comparative performances of the tools. To the astonishment of Messrs. Taylor and White, the steel which they had decided on as being the best, made the poorest performance in the comparative test. This lead Messrs. Taylor and White to experiment with the heat treatment of the steel which they thought would give the best results, and they soon discovered, again contrary to all previous experience, that steels of the Mushet type could be heated nearly to their melting point without burning, and could be hardened from this temperature. It was found that the steel hardened in this manner was many times superior to the steel as usually hardened. Thus to Messrs. Taylor and White is usually given the credit for the discovery of High Speed Steel. Their discovery was really the manner of heat treatment and not of the steel itself and it is noticeable that Messrs. Taylor and White were never able to obtain patents on High Speed Steel. Prior to the time of Messrs. Taylor and White's discovery of the high heat method of treating Mushet and self-hardening steels, Mr. A. G. McKenna, then connected with the Firth Sterling Steel Company had advocated the high heat treatment and even published articles to this effect. As soon as the high heat treatment began to be generally learned, keen rivalry developed in the experimenting with both the heat treatment and analysis of steels of the Mushet and self-hardening type.

The analysis of the self-hardening steel marketed as "Robert Mushet's Special" was approximately as follows: Carbon 2.00, Tungsten 5.00, Chrome 0.5, Manganese 2.5, Silicon 1.3. Other steels of the Mushet type that were marketed in America about 1900 have the following analysis:

<table>
<thead>
<tr>
<th>C</th>
<th>W</th>
<th>Cr</th>
<th>Mn</th>
<th>Mo</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.67</td>
<td>7.60</td>
<td>3.70</td>
<td>4.6</td>
<td>.00</td>
</tr>
<tr>
<td>2.30</td>
<td>5.90</td>
<td>.60</td>
<td>1.35</td>
<td>.00</td>
</tr>
<tr>
<td>1.20</td>
<td>8.05</td>
<td>2.10</td>
<td>.35</td>
<td>.00</td>
</tr>
<tr>
<td>1.40</td>
<td>.00</td>
<td>3.00</td>
<td>1.60</td>
<td>4.50</td>
</tr>
</tbody>
</table>
As will be noticed the composition of the self-hardening steel as made by the different Companies were exceedingly variable. This type of steel although of remarkable cutting and wearing qualities was not adapted for finishing or fine work where the cut had to be smooth. This, of course, was due to the coarse grain of self-hardening steels which did not allow the tools made from this steel to take a keen cutting edge such as would leave a good finish, so this steel was used chiefly for tools used for coarse and heavy work. This difficulty, however, was rapidly overcome as the analysis of the new steels were changed.

Muschet Steel which was the forerunner of High Speed Steel gradually gave way to self-hardening steels of similar analysis which in turn gave way to steels which we know to-day as High Speed Steels. Thus it might be said that High Speed Steel grew during the years from 1896 to 1902 and were not invented by any one man or Company. In 1902 we find that the manufacturers was still at sea to know what analysis was best with which to make their High Speed Steel Conform. Thus in 1902 we find a number of manufacturers marketing High Speed Steel of the following analysis:

<table>
<thead>
<tr>
<th>No.</th>
<th>C</th>
<th>Mn</th>
<th>Cr</th>
<th>W</th>
<th>Mo</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.65</td>
<td></td>
<td>4.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.42</td>
<td></td>
<td>4.95</td>
<td>10.75</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.57</td>
<td>0.143</td>
<td>3.30</td>
<td>11.58</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.75</td>
<td></td>
<td></td>
<td>19.50</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.37</td>
<td></td>
<td>5.10</td>
<td>13.85</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.62</td>
<td></td>
<td>6.50</td>
<td>21.06</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.84</td>
<td>0.07</td>
<td>2.76</td>
<td>11.25</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.56</td>
<td></td>
<td>2.95</td>
<td>9.74</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>0.60</td>
<td>0.30</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

From this time (1902) until some ten years later at short intervals of time announcements have come from different sections of the globe of new and startling discovered of high speed steel. A large number of these so called discovered within the last few years have been announced in England without their knowledge that many of their "startling" discovered were made a few years before in America, but notannounced to the world as they had proven failures. A large number of elements singly and in combination have been added to high speed steel with the hopes that they would prove beneficial. The only outstanding element that has been added to the composition of high speed steel after its introduction by Messrs. Taylor and White is Vanadium.

Vanadium has truly been highly beneficial to high speed steel. Aside from its wonderful properties as a scavenger and cleanser, it has increased the cutting efficiency of high speed steel with an increase in toughness. Vanadium was first added in about 1902, but even in 1910 many companies were debating its worth and writers of that
period even stated that vanadium .20 was not beneficial and even detrimental. Vanadium, as we all know, is to-day in this country considered almost as much of a necessity in the composition of high speed steel as some of the other elements. Yet in France, Switzerland and several other European countries little or no vanadium is added to their high speed steel. This, however, may be explained not from the fact that they do not think it would be beneficial, but that its scarcity and price in these countries have warranted its use.

Of the many other elements that have been tried at many times in the composition of high speed steel, molybdenum is probably the most prominent, and has received the greatest amount of discussion. Molybdenum was, as we all know, used in self hardening steels during the period of 1890 & 1900, and also was one of the first elements used and tried in the first high speed steels. It has been tried by a large number of companies since then with very erratic results. Molybdenum from a chemical standpoint should have about the same effect in steel as tungsten, using about one-half as much owing to its atomic weight being about one-half that of tungsten. This statement holds true, but other factors have caused its use to be abandoned in high speed steel. The most prominent of these factors is the characteristic demolybdenization, which so readily takes place; a steel containing a large amount (three per cent. or over) of molybdenum when heated to a forging temperature will give off a yellowish fume which is molybdenum oxide volatilizing from the steel. Moreover finished tools can not be made out of a molybdenum high speed steel and heat treated afterwards owing to this demolybdenization which takes place to a great depth and is similar in action to the decarburization of a carbon steel. During the last few years the foreign countries especially England have made startling statements for the use of molybdenum in high speed steel when most of these steels that they claimed so splendid were proven failures a few years ago in America when compared to our best high speed steels.

It might be worthy of note, however, that during the last two or three years a steel containing a small amount of molybdenum (usually under one per cent.) with or without chromium, nickel and vanadium has proven very good as a structural steel, and for use in automotive and airplane parts. In these steels molybdenum appears to increase their toughness.
Other elements too numerous to mention have been tried in high speed steel with more or less ungratifying results. During the world war, the element, tungsten, became scarce and its price rose to unusual heights. This caused several of the American companies to decrease the amount of tungsten in their high speed steels with a slight increase in the amount of vanadium, which at that time was more plentiful than tungsten, and which accordingly made the steel cheaper to manufacture. This steel, when quenched from a temperature of some 2150 - 2200 deg. Fahr., gives probably as good results as some high speed steels when treated from the same temperatures, but results that are noticeably inferior to first quality high speed steel when quenched from 2300 deg. Fahr. and above. This fact and the fact that some of the smaller shops not properly equipped seem to have a preference for a low heat treatment has caused this warborn steel to be continued by a few mills.

The greatest development of late in the high speed steel industry has not been so much in the analysis of the steels as it has been in their manner of manufacture and in their heat treatment. The electric furnace introduced in about 1910 and which began to find general usage in the American tool steel industry in 1915 has been one of the notable advances in the manufacture of high speed steels; for in the electric furnace a uniformity and refinement of the steel can be attained that had never been dreamed of in the Crucible Process, which had been in use for years at that time.
Two general methods of melting high speed steel are in universal use to-day, the first of these methods the crucible process has been used for centuries, while the second method that of the electric process has been used only since about 1910, but has now widely replaced the crucible method.

CRUCIBLE METHOD-

The crucible method of steel manufacture is by far the simplest of all processes in use, but at the same time is by far the most expensive, due to the small units which are handled and to the large consumption of labor. Briefly the process consists of the placing of muck bar, ferro-alloys and carbonaceous material in a graphite or clay crucible; then placing this crucible in a furnace and melting its contents; then the casting into ingots of the liquid steel.

The crucibles which are generally used in the U. S. A. are made of a mixture containing one-half clay and one-half graphite though this proportion varies. Sometimes these graphite pots are lined with a fire clay or refractory material. The crucibles used in most foreign countries are clay. Each type of crucible has its advantages and disadvantages.

When high speed steel is made in graphite pots, it absorbs carbon from the pot and as the amount absorbed varies under different conditions, it is difficult to control the amount of carbon entering into the steel. Graphite pots, however, will hold readily a 100# charge and will usually last for 6 heats, while clay pots are not strong enough usually to hold over a 50 or 60 pound charge, but the analysis of the steel can be better controlled as no carbon is absorbed from the crucible.

The amount of iron, ferro-alloys and carbon as desired, is carefully weighed into the crucible in the mixing room, and the formula for the steel once adopted is religiously followed in order to obtain as uniform melts as possible.

The melting furnace in which the pots are placed may be of several types, but for high speed steel melting the reverberatory type with generators and checkers is generally used. This type of furnace lends itself to easy heat regulation through a system of valves and dampers. Gas is used as fuel. The furnace is usually divided
into a number of compartments or holes, and each hole will contain space for from four to six crucibles. The number of holes depends upon the capacity desired.

High speed steel can be melted in the crucible furnace in about four hours; then the steel is allowed to remain some thirty minutes longer in order to "kill" or "dead melt" it, as the steel must be quiescent when poured or blowholes will result in the ingots.

As soon as the steel is "dead melted" the crucible is "pulled" and the small amount of slag which has formed over the molten steel is skimmed off; the contents of the crucible are then usually emptied into the mold which is normally of such size as to hold only the contents of one crucible. If a larger ingot is desired, several crucibles may be poured at the same time into a "runner" which empties into the mold thoroughly mixing the contents of the several crucibles. Sometimes the contents of a number of crucibles are poured into a ladle and then the steel is teemed from the ladle into the molds.

**ELECTRIC PROCESS—**

The electric process of melting high speed steel became a commercial success in about 1910, and from that time until the present the process has moved forward in leaps until now it has widely replaced the crucible process. The process is not simple, but owing to large units that can be handled and to the control of the analysis of the product, the process as compared to the crucible method is cheap.

The early difficulties in the manufacture of electric steel were not so much in the compounding of the steel as mechanical and heat difficulties, due to the poor design of the furnaces. The first furnaces used were of the Stassano design in which the heat is generated exclusively by the electric arc formed above the material to be melted. Difficulties too numerous to mention in this short outline prevented this furnace from becoming a success, so that to-day there are no Stassano furnaces in operation in the U. S. A. A furnace of the same principle as the Stassano but of different design, known as the Rennerfelt has found a limited usage, there being eighteen of these furnaces in operation in the U. S. A. at present. However, it was only shortly after the introduction of the Stassano furnace that the Heroult came into use. This furnace represents the most successful of the electric furnaces. The Heroult is of such design that the electric arc is formed between the material to be melted and
the electrodes. The Heroult patents have now expired and there are a number of furnaces in the market embodying all of the Heroult principles and even exceeding the Heroult furnace in mechanical construction. In January 1922 there were one hundred sixty four Heroult furnaces in the steel industries; these furnaces ranging in size from one-half to forty tons.

A brief description of the operation and construction of a Heroult furnace used for melting high speed steel follows: The bottom and sides slightly above the slag line are made of rammed magnesia and magnesia brick on which basic slag can be made for the removal of sulphur and phosphorus. The upper walls and roof are made of silica brick. Three twelve-inch electrodes enter vertically through the roof and are held by water-cooled copper rings. These electrodes are automatically controlled so as to give the desired heat. Each electrode arcs with the charge which acts as a conductor.

Following is a typical charge sheet which shows the material charged and produced:

<table>
<thead>
<tr>
<th>Grade - Red Cut Superior</th>
<th>Heat No. 3276</th>
<th>Date - 9/16/20.</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANALYSIS REQUIRED</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C. Si. Mn. S. P. W. Cr. V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>.66 .20 .23 .0 .0 18.00 3.85 1.00</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>LIMITS</th>
<th>.63/.73</th>
<th>.10/.35</th>
<th>.15/.35</th>
<th>.03 max.</th>
<th>.03 max.</th>
<th>17.50/18.50</th>
<th>3.65/4.15</th>
<th>.85/1.20</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Charged</th>
<th>Produced</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red Cut Superior Bar Ends</td>
<td>Ingots cast</td>
</tr>
<tr>
<td>Red Cut Superior High Speed Scrap</td>
<td>Scrap</td>
</tr>
<tr>
<td>High Speed Turnings</td>
<td>No. Size</td>
</tr>
<tr>
<td>Low Tungsten Scrap</td>
<td>4 6&quot;</td>
</tr>
<tr>
<td>Ferro-Silicon</td>
<td>8 7&quot;</td>
</tr>
<tr>
<td>&quot; Manganese</td>
<td></td>
</tr>
<tr>
<td>&quot; Chrome High Carbon</td>
<td></td>
</tr>
<tr>
<td>&quot; Tungsten</td>
<td></td>
</tr>
<tr>
<td>&quot; Vanadium</td>
<td></td>
</tr>
<tr>
<td>Low-phos. Iron</td>
<td>Time for Heat</td>
</tr>
<tr>
<td>Limestone</td>
<td></td>
</tr>
<tr>
<td>Lime</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CHEMICAL ANALYSIS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1 .42</td>
<td></td>
</tr>
<tr>
<td>2 .48</td>
<td></td>
</tr>
<tr>
<td>3 .59</td>
<td></td>
</tr>
<tr>
<td>Final .69 .27 .35 Tr. .018</td>
<td></td>
</tr>
<tr>
<td></td>
<td>17.90</td>
</tr>
<tr>
<td></td>
<td>3.77</td>
</tr>
<tr>
<td></td>
<td>.96</td>
</tr>
</tbody>
</table>
All the materials shown are charged at the beginning excepting the ferro-manganese, ferro-silicon, and ferro-vanadium and one hundred fifty pounds lime used for the second slag. The above alloys are not added until immediately before pouring, due to their quick oxidation.

As soon as the charge is molten the slag is skimmed off; a sample is taken for analysis; a new slag is added; additions are made to get desired analysis and as soon as the steel is "killed" the silicon, manganese and vanadium are added and the steel is poured into a ladle from which it is teemed into molds.

After casting into ingots the steel is cooled slowly to prevent clinks in the ingots and the ingots are then stored for future use.

Forging.

Forging in addition to giving the steel the desired shapes and sizes, thoroughly breaks up the cellular structure so persistent in high speed steel, and also often discloses defects in the steel that must be eliminated.

The ingots are first preheated and then heated to a temperature of 2150° F. from which temperature they are forged either with billets for subsequent operations or into finished sizes ready to be annealed and machined. The amount of reduction given an ingot in forging has great effect upon the subsequent quality of the steel and this is more fully discussed under the metallography of high speed steel. It has been conclusively shown that a large number of light blows with the hammer produce a much better structure in the steel than a small number of heavy blows. Also it has been found that high speed ingots cannot be successfully pressed into billets, or rolled into billets through a blooming mill, thus the forging of high speed steel becomes practically a fundamental operation when it is necessary to produce material of the highest quality. After forging the ingots into billets or finished sizes the steel is again cooled very slowly to prevent "clinks" or cracks from developing.

Rolling.

From the hammer shop the billets are sent to the rolling mill where they are charged into a furnace at a temperature of about 2100° F. They are thoroughly soaked at this temperature and rolled into the desired shapes and sizes. The bars should be
through the rolls before the temperature has dropped to less than 1750° F. or the deformation may be too great causing cracks to form. The rolling of high speed steel presents no unique problems. However, unusual shapes are sometimes required such as drill and reamer sections and it requires great skill in the roller to produce these sections uniformly and true to size.

Annealing.

Those sizes that were finished at the hammers and at the rolls are sent to the annealing department. Here the steel is packed in large containers, usually pipes with carbonaceous material to prevent the decarburization of the bars in the annealing operation. These containers are then sealed and are charged with the annealing furnace which is at a low heat. The temperature of the furnace is then slowly raised until it reaches from 1550° F. to 1700° F. depending upon the plant practice. This temperature is maintained from six to twelve hours, and then this steel is allowed to cool with the furnace usually at the rate of about thirty to forty degrees F. per hour until a temperature of some 1100° F. is reached when the containers may be withdrawn from the furnace and cooled to normal temperatures.

The containers are the opened and the high speed steel now in the annealed condition is sent to the inspection department.

Inspection.

The inspection department rightfully has control over the product not only after it is finished, but during process of manufacture. This consists in inspecting the ingots, the billets, etc., as they move from one operation to another, and of course, the inspection of the finished material. Each bar is inspected for pipes, seams and decarburization. Also a test is usually made on a number of bars of each lot as a test for annealing.

After the material has passed the inspection department, it may be sent directly to the customer who will then subsequence make it into tools of some class, or it may be racked for future consumption.
Although heat treatment may not be a purely manufacturing operation, high speed steel untreated is useless, therefore the importance of this operation cannot be overestimated.

Probably there exists no subject in steel metallurgy that has been more fully discussed and written on, than the heat treatment of high speed steel. To give a resume of the suggestions that have been made in regard to this subject would fill volumes.

The most general approved method of treating high speed steel is as follows:

Preheat the steel to 1500 - 1550° F. Transfer to high heat furnace which is at a temperature of 2300 - 2325° F.

Quench in oil Draw to 1100° F.

Such a procedure the very simple allows of multitudinous deviations, some of which may be beneficial to the steel when used for certain purposes, but in general the above procedure is recognized as the best.
Future developments in the quality of high-speed steel might be expected not so much in analysis as in methods of manufacture, thus the study of the constitution of high-speed steel has become fundamental if the highest quality and most uniform product is to be obtained.

How many men have had the experience of two pieces of high-speed steel of the same analysis and supposedly of the same heat treatment, where one piece gave results much better than the other on the same job? Why? Surely there is a reason. And that reason undoubtedly is enclosed in the history of those pieces of steel for it is their history that determines their quality; and a study of their history is a study of their constitution.

The use of the words "high-speed steel" in this paper refer to a steel of an approximate analysis of:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>.65/.70</td>
</tr>
<tr>
<td>Tungsten</td>
<td>17.50/18.50</td>
</tr>
<tr>
<td>Chrome</td>
<td>3.75/4.15</td>
</tr>
<tr>
<td>Vanadium</td>
<td>.90/1.25</td>
</tr>
</tbody>
</table>

which analysis is recognized as the analysis of the first quality high-speed steels. Moreover, when reference is made to the ingot or billet, etc., it infers high-speed steel.

The word Metallography used in the title of this paper, "The Metallography of High-Speed" is used in its broader sense; under this title we are including the critical points and constitution of high-speed steel with a discussion of whatever experiments and factors that bear a direct relation to these two subjects.

There have been but few systematic investigations made on the subject of the constitution of high-speed steel, although there has been a reasonably large number of investigations made on the transformation points, the hardening and drawing temperatures, efficiencies of various analyses, uses, magnetic properties, etc. A paper presented by Honda and Murakami at the Iron & Steel Institute in May, 1920, represents probably the best that has been written on the constitution of high-speed steel and is worthy of consideration in detail, but some of the statements they make are but feebly supported by the evidence they present. Their experiments consisted essentially of a study of three series of high-speed steels, the first in which the percentages of tungsten and chromium were constant with the percentage of carbon as a variable, the second with the percentages of tungsten and carbon constant with the percentage of chromium as a variable, and the third with the percentages of chromium and carbon constant with the percentage of tungsten as a variable. Honda has deduced most of his changes in structure in heating and cooling by magnetic analysis. A steel containing
.62 carbon, 5.12 chromium and 17.20 tungsten is taken as a typical example and in the normal condition he states that this steel is composed of iron-dissolving tungstide, free tungstide, chromium carbide and tungsten carbide all in a free state.

Here is shown the manner in which they would write this structural constitution:

\[
(\text{Fe}) + (\text{Fe}_2\text{W}) + [\text{Fe}_2\text{W}] + [\text{Cr}_4\text{O}_3] + [\text{WO}] \quad (1)
\]

Above the Acl-5 point both carbides dissolve in the austenite and then the constitution is as follows:

\[
[\text{Fe}_2\text{W}] + [(\text{Fe}) + (\text{Fe}_2\text{W}) + (\text{Cr}_4\text{O}_3) + (\text{WO})] \quad (2)
\]

The constituents in solid solution are enclosed by parenthesis and those in a free state by brackets. As the temperature increases above the Acl point the chromium carbide dissociates as follows:

\[
2\text{Cr}_4\text{O}_3 = \text{Cr}_3\text{O}_4 + 5\text{Cr} \quad (3)
\]

Then as the affinity of carbon for chromium seems to be stronger than its affinity for tungsten, some of the chromium produced by the dissociation of \(\text{Cr}_4\text{O}_3\) will react on the tungsten carbide as follows:

\[
3\text{Cr} + 2\text{WC} + 4\text{Fe} = \text{Cr}_3\text{O}_2 + 2\text{Fe}_2\text{W} \quad (4)
\]

hence at the higher temperatures the structure is

\[
[\text{Fe}_2\text{W}] + [(\text{Fe}) + (\text{Fe}_2\text{W}) + (\text{Cr}) + (\text{Cr}_3\text{O}_2) + (\text{WO})] \quad (5)
\]

But the cooling from the temperature at which this structure exists, the lowering of the transformation point is caused by the presence of dissolved carbide \(\text{Cr}_3\text{O}_2\) in austenite containing chromium and tungstide, thus the steel cooled in normal temperatures has the same constitutional structure that existed at the high temperatures, that is

\[
[\text{Fe}_2\text{W}] + [(\text{Fe}) + (\text{Fe}_2\text{W}) + (\text{Cr}) + (\text{Cr}_3\text{O}_2) + (\text{WO})] \quad (5)
\]

If the steel be now heated again the dissolved carbides separate and the reactions (3) and (4) proceed from right to left and \(\text{Cr}_4\text{O}_3\) and \(\text{WO}\) are again formed.

To substantiate these views, Honda says further: First, in the magnetic analysis, the chromium effects the lowering of transformation in the presence of carbon, and if the carbon content is .6 per cent, about 3% of chromium is sufficient for the lowering or the self-hardening; a further addition of chromium not being effective, unless the carbon content is increased. Second, the resistance to tempering of hardened steels depends on dissolved \(\text{Cr}_3\text{O}_2\) and tungstide in iron containing chromium as in the steels of series II where the percentages of chromium is the variable; as the percentage of chromium increases to 3.32 percent, the maximum increase of magnetization of the range of 400° C gradually decreases and that of 700° C increases, but a further increase of chromium has no effect. While in steels of series I with the percentage of carbon as a variable,
as the carbon content increases from .57 to 1 percent, the maximum increase of magnetization at 700° C becomes less, showing that the resistance to tempering increases. Third, that the maximum increase of magnetization at about 700° C due to tempering at first increases as the maximum temperature of previous heating increases from 401 point to 1000° C, but decreases as the temperature further increases. This would show that if the maximum temperature of previous heating is below 1000° C., the quantity of the dissolved carbide Cr₂C₂ is very small and slowly increases with the rise in temperature and thus by tempering, the separation of the carbide slowly increases. Fourth, that in chromium steels without tungsten there exists at high temperatures some dissociated chromium and Cr₂C₂ as shown by the lowering of the transformation by a quick cooling from 900°, but as tungsten is added to the steel some tungstate is formed and this tungstate seems to prevent the recombination of chromium and Cr₂C₂ thus causing the lowering of the transformation.

Reference will be made to this theory later; however, it is interesting to note here that the results given have been deduced nearly altogether from magnetic analysis.

(2)
Edwards and Kidkawa briefly discussed the constitution of high-speed steels in a paper before the Iron & Steel Institute in 1915, but they made no attempts to give exact chemical composition of the constituents. Prof. Arnold studied the constituents of high-speed steels by analyses of residues and his paper presented also before the Iron & Steel Institute in 1919 is highly interesting.

(3)
Other papers by Honda and Murakami and by Hultgren on tungsten steels lend an interesting aspect to the constitution of high-speed steel. Papers by Carpenter, Yatsevich, and Andrew and Green fully discuss the critical points in high-speed steel, while a large number of other investigators have likewise contributed to the knowledge of this phase of high-speed steels.

In presenting this paper we have found it necessary to group our experiments under a number of headings. These headings will be taken up not in the order of their importance, but in such an order that we believe will prove the clearest.
2 - CRITICAL POINTS

A number of heating and cooling curves have been made, a few of which are reproduced here. These points were derived by using the differential method. The rate of heating and cooling was practically the same for all the specimens. The steels used in obtaining the curves was in the annealed state and had an analysis as follows:

<table>
<thead>
<tr>
<th>Element</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>.69</td>
</tr>
<tr>
<td>Silicon</td>
<td>.23</td>
</tr>
<tr>
<td>Manganese</td>
<td>.29</td>
</tr>
<tr>
<td>Sulphur</td>
<td>.008</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>.018</td>
</tr>
<tr>
<td>Tungsten</td>
<td>18.55</td>
</tr>
<tr>
<td>Chromium</td>
<td>5.82</td>
</tr>
<tr>
<td>Vanadium</td>
<td>1.01</td>
</tr>
</tbody>
</table>
It will be noticed in all the heating curves that there are distinct
decaesence points beginning at a temperature of about 1400° F. and 1550° F. and reaching a maximum respectively at the temperatures of 1420° F. and 1570° F. The upper of the two points begins considerably more intensely than the lower, and is also more prolonged. These points are extremely constant, and Sauveur suggested that since the two points occur within such narrow limits it is possible that they do not indicate two distinct transformations but represent two phases or stages of the same transformation. This view seems untenable since if the two points represented two phases of the same transformation, a change in the heating rate would alter the constancy of the positions in which they occur; also if the heating was stopped between the two points the transformation already begun would be likely to go to completion by holding the temperature; this however is not the case. In curve No. 1 heating was stopped at 1700° F. and the temperature was allowed to fall immediately. A distinct recaesence takes place beginning at 1420° F. and reaching a maximum at 1370° F. while at 790° another feeble recaesence point may be discerned that likely would remain unnoticed if it were not for the other diagrams that develop this point so clearly. In diagram No. 2 heating was stopped at 1750° and cooling allowed to commence at once. The two recaesence points seems to be of about the same intensity at their maximum but the higher point is much more prolonged.

In diagram No. 3 where the heating was stopped at 1600°, the upper point is barely noticeable while the lower point is intense. In curve No. 4, heating was stopped at 1650° and the curve thus developed is practically the same as in No. 3, where the heating was stopped at 1600° F. In curve No. 5 the heating was stopped at 1660° but the specimen was held at this temperature for thirty minutes before cooling started. Two distinct points are noticeable, while in curve No. 1 the lower point can barely be noticed yet the specimen was heated to a temperature 50° higher. In curve No. 6 the temperature was likewise held for thirty minutes this time at a temperature of 1700° F. and the two recaesence points have about the same maximum intensity. This curve corresponds closely to No. 2 where the maximum temperature reached was 1750° F. The rate of heating and cooling the specimen was practically the same in producing each curve.

It will be noticed that the two recaesence points remain fairly constant and as one is suppressed the other is intensified, indicating two distinct points, and not the shifting of one point to another position.

The transformation taking place therefore at the upper decaesence point apparently does not go to completion upon reaching the temperature at which the point is
indicated on the diagram but depends upon the temperature reached above this point and the time held at this temperature. This is further substantiated by the prolonging of the point after the maximum has been passed.

The first decalssence point thus seems to result from the carbon contained in the sorbite going into solution or the formation of austenite, while the upper decalssence point results from the commencing of the solution of the tungstides which depends upon time and temperature for completeness, in proof of which are shown here two micrographs, Nos. 1 and 2, of the same piece of high-speed steel, No. 1 of which was quenched from 2100° F., and the other from 2380° F.

A comparison shows how much more completely the tungstides have gone into solution in the specimen quenched from the higher temperature.

The recalssence points do not permit of an easy an explanation. It is feasible, however, that the upper point represents the transformation of the austenite, and the lower point the forming of the tungstides from solution. This being the reverse of what is expected in most steels where the last transformation to take place on heating is the first transformation to take place on cooling. Yet, as shown by the diagrams, as the upper recalssence point is suppressed, the lower point is intensified, and as the lower point is intensified more tungstides have been dissolved either by heating to a higher temperature or by holding at a temperature above the upper decalssence point.
It would then seem that as the tungstides went into solution the transformation of the austenite would be retarded and the upper recrystallization point would occur at a lower temperature, but here it is actually suppressed more and more by the solution of the tungstides until no point exists. As the solution of tungstides becomes greater the lower recrystallization point increases in intensity indicating a direct relationship, or that the lower point is where the tungstides form from the solid solution.
Bearing more or less direct relation to the critical points of high-speed steel is what is termed "the phenomenon of secondary hardness" which we do not consider a phenomenon at all, but a very natural occurrence. Mr. Howard Scott classified a number of quenched specimens into two groups one of which exhibits secondary hardness and which were quenched from a temperature above 2000° F., and the other which did not exhibit secondary hardness and which were quenched from a temperature less than 2000° F. Here is shown a chart which bears out his classification very well:

![Chart showing Brinell hardness vs. cooling temperatures](chart.png)

A microexamination of a number of specimens shows that the secondary hardness increases in a direct proportion to austenization. So it is well that consideration be given here to the effect of the different elements on secondary hardness or in truth on austenization.

A carbon steel containing 1.10 carbon may be hardened by quenching in water from some 50° above its critical point to obtain a Brinell hardness of nearly 700, yet it does not show a secondary hardness on tempering, and its structure is plainly martensitic.

A steel containing .97 carbon and 4.05 chromium with no tungsten can be hardened in air from 1650° F., and will exhibit extreme hardness if quenched in oil but such a steel does not show a perceptible secondary hardness and a micro-examination of the hardened steel shows a martensitic structure. Moreover, in making cooling curves of a steel with a variable chromium content, the maximum temperature from which cooling begins does not have an appreciable influence on the position of the recrystallization points.

A steel containing .68 carbon and 15% tungsten when quenched in oil from 2000° C. shows only a hardness of about 500 Brinell but does exhibit a slight secondary
hardness. However in such a steel most of the tungstides remain undissolved regardless of the temperature from which quenching takes place. The temperatures from which cooling curves are made on such a steel do influence the position of the recrystallization points.

Thus it is a combination of the three elements—carbon, chromium and tungsten (not one, nor a combination of two), that depress the critical range to such a degree that an austenitic steel can be produced by practical heat treating methods which being tempered to the harder constituent martensite produces secondary hardness.

It is a natural result, and seems unusual only since austenite is not produced in most steels by commercial heat treatment.
4 - ETCHING REAGENTS

We have used a number of etching reagents for the development of the microstructure of high-speed steels with various results. An alcoholic solution containing from 1% to 4% nitric acid has been used on annealed or hardened and highly drawn specimens. A 4% solution reacting on annealed specimens requires only some thirty to forty seconds to fully develop the structure, while the same solution reacting on a hardened and highly drawn specimen requires from one and one-half to three minutes to develop the structure. We have not found, however, nitric acid as valuable an etching reagent for annealed specimens as an alcoholic solution diluted with from 10% to 15% water and saturated with picric acid. This solution develops the matrix in greater detail than does nitric acid as shown by micrographs Nos. 3 and 4:

Neither of the two reagents colors the tungstides and they remain clearly revealed as white embedded globules. On specimens hardened and not drawn an alcoholic solution containing from 6% to 8% nitric acid reacting on the specimen from three to six minutes will clearly develop the polygonal structure that is characteristic of hardened high-speed steel, while on specimens of this type picric acid reacts exceedingly slow, and even after an immersion of an hour the structure is but faintly developed.
Micrographs Nos. 5 and 6 are of hardened specimens etched with an alcoholic solution of nitric acid:

An alcoholic solution containing from 2% to 5% nitric acid and saturated with picric acid does not develop the structure of annealed specimens as well as the picric acid alone, and seems to offer no advantage in the etching of the hardened specimens over a nitric acid solution. It is readily apparent when using these etching reagents that the time required for the development of the structure is a direct indication of the heat treatment the steel has received, and many times valuable information can be obtained concerning the treatment of the steel by timing the etching.

Heat tinting will develop the structure of annealed specimens as the result of a thin coat of iron oxide forming over the matrix while the embedded tungstides remain unchanged. This is shown by micrograph No. 7:

No. 7
500 X
Heat Tinted
We have not found any advantage in using this method for the development of the microstructure, as the matrix is not as clearly defined as when using picric acid.

A solution made up of 30% commercial hydrogen peroxide and 10% sodium hydrosulphite and the remainder water, proved valuable for etching the tungstides a dark brown or black while leaving the matrix apparently unetched. This solution works equally well on all specimens, regardless of the condition in which they exist. It is necessary, however, to make up the solution shortly before using as it disintegrates rapidly and loses its strength. A specimen etched with this solution is shown by micrograph No. 9. The etching time is from ten to fifteen minutes and as only the tungstides are etched the time remains the same on all specimens regardless of their heat treatment.

Another solution from which etching results can be obtained quite similar to the solution just mentioned is made up of ten (10) grams Potassium or sodium hydroxide and ten (10) grams $K_2Fe(CN)_6$ in 100 cc. water. Practically the same results were obtained by using this solution as the sodium hydroxide - hydrogen peroxide solution. This solution will etch the tungstides much more rapidly, as the etching time is only from thirty to fifty seconds. Another advantage this solution has over the sodium peroxide solution is its stability, as it may be preserved from three to four months without apparent decomposition. A specimen etched with this solution is shown by micrograph No. 9:
The question of nomenclature of the constituents of high-speed steel other than the tungstides or carbides often arises, and you have probably asked yourself whether or not the nomenclature of the constituents of a carbon steel are applicable to a steel that is really approaching an alloy, for 25% of the composition of high-speed is not iron. From evidence that follows and considering the breadth of the definitions of the nomenclature of the constituents of carbon steel, we believe that the same nomenclature is applicable to the constituents of high-speed steel.

Austenite as it is defined is the solid solution of iron and carbon as it exists above the transformation range or as preserved at lower temperatures by rapid cooling or by the presence of retarding elements. It may contain carbon up to the saturation point, namely 1.7% C. It is polyhedral and is darkened less by the acid etching reagents than troostite, sorbite and martensite. Its hardness is variable depending on the state in which it is preserved, but is usually never considered as hard as martensite. It is very slightly magnetic and does not show as great a volume change in passing from pearlite or sorbite into austenite, as does martensite.

Considering the austenite of high-speed steel, it is primarily a solid solution of iron and carbon plus dissolved tungsten, chromium and vanadium. That it is polyhedral is evidenced by any micrograph of hardened high-speed and is shown here by micrographs Nos. 10 and 11:

![Micrographs of austenite](image)

That it is darkened less by the acid reagents than are martensite, troostite and sorbite is shown by the etching time necessary for etching steels containing these constituents and previously mentioned. Its hardness is not as great as that of martensite as shown by diagram No. 1. That it occupies a smaller volume than does
Martensite is evidenced by this diagram, No. 2, of the change in specific gravity by drawing hardened high-speed steel:

![Graph 1](image1)

![Graph 2](image2)

No. 1.

The austenite of high-speed steel is also feebly magnetic, and here are two diagrams, Nos. 3 and 4, showing the changes produced in hardened high-speed steel in maximum and residual magnetic induction by drawing:

![Graph 3](image3)

![Graph 4](image4)

No. 3

Next, considering martensite which is defined as the first stage in the transformation of austenite characterised by needle-like structure and great hardness. Its hardness exceeds that of any other constituent produced in the transformation of austenite with pearlite. It is magnetic. It etches darker with acid reagents than austenite but lighter than troostite. It represents a metastable condition in which the steel is caught during retarded transformation as austenite is passing into a mixture of ferrite and cementite.
Comparing the martensite as developed in high-speed steel, (shown by micrograph No. 12):

It is certainly the first state in the transformation of austenite, as characterized by its increasing hardness, greater volume, and considerably higher values for residual and maximum magnetic induction. It is likewise distinguished by its needle-like structure and high-speed steel existing in the martensitic state is in its hardest state. It etches darker than austenite but does not etch as rapidly as troostite or sorbite. That it represents a metastable condition is evident, since by quenching high-speed from a high temperature austenite is produced which can be readily changed into martensite by heating to 1100°F., while heating to a higher temperature destroys the martensite.

Considering next in order, troostite, it is defined as the stage in the transformation of austenite that follows martensite and precedes sorbite. That it is an uncoagulated conglomerate, and that the degree of completeness of the transformation it represents is not definitely known and probably varies widely. It is not always easily and definitely discernible under the microscope, as it occurs in an irregular manner. Acid etching reagents darken it more than martensite or sorbite, one or both of which usually accompany it. Its hardness is intermediate and its magnetic properties are indefinite.

Troostite as it should exist in high-speed steel is the most indefinite of the constituents in the transformation of austenite. Under the microscope it is ex-
ceedingly difficult to distinguish and here are shown two micrographs, Nos. 13 and 14, that bear evidence of this fact:

No. 13 is of annealed high-speed having a Brinell hardness of 228, while No. 14 is of hardened high-speed steel drawn to 1450°F and has a Brinell hardness of 444. There is practically no difference in the appearance of the matrix. This micrograph of the specimen drawn to 1450°F was chosen as representative of the microstructure that apparently exists after the disappearance of the martensite. This structure can hardly be called sorbite, as sorbite in high-speed steel represents a stable condition, while the physical and magnetic properties co-existing with this structure vary to a great degree as a result of heat treatment. Its properties are intermediate as are the properties of troostite in carbon steel. Acid etching reagents however, apparently darken it to about the same degree as sorbite in high-speed steel. That it represents a step in the transformation of austenite is apparent from its physical and magnetic properties which are intermediate. Thus even though microscopically troostite cannot be satisfactorily distinguished, in view of the broadness of the definition of the term, there is justification of giving the name troostite to that structure that exists between martensite and stable sorbite.

Sorbite as defined is the stage in the transformation of austenite following troostite and preceding pearlite. It is usually considered as an uncoagulated conglomerate of pearlite with ferrite or cementite depending on the carbon content of the steel, but that it may contain some incompletely transformed matter. It is not resolvable under the microscope and cannot properly be represented on the equilibrium diagram, hence it represents a metastable condition.
Considering the sorbite of high-speed steel as shown by micrograph No. 15, it follows troostite:

\[
\text{500 X} \quad \text{No. 15.} \quad \text{Picric}
\]

as we have so considered it in the transformation of austenite. It is not resolvable under the microscope. It represents a stable condition and in this respect resembles the pearlite of carbon steel, and would therefore be represented on the equilibrium diagram below, \(\text{Ae}_1\). This is evidenced by the fact that a resolvable constituent of high-speed steel similar microscopically to the pearlite of carbon steel is not to be obtained. Regardless of the treatment that may be given to high-speed steel, sorbite apparently represents the end in the transformation of the austenite, thus becoming a stable constituent and deserving of representation on the constitutional diagram where the pearlite is represented in carbon steels.

The pearlite of carbon steels partly corresponds to the sorbite of high-speed steel as just mentioned, and not bearing a true resemblance to any constituent in high-speed steel will not be described.
The chemical composition of the matrix and of the embedded globules of high-speed steel in its different states presents an interesting study that few investigators have attempted. Honda's theory that in the annealed condition high-speed steel was composed of iron-dissolving tungstide, free tungstide, chromium carbide and tungsten carbide is difficult of conception in view of some of the following evidence.

Every manner of etching the specimen that has been tried results in all the globules having exactly the same appearance, while if the globules were of different composition it seems that some of the various manners of etching would have attacked them differently; second, from preliminary observations the melting points of Fe₂W, Cr₄C and WC vary widely; we may then assume that their rate of absorption or solution by the iron-dissolving tungstide would vary likewise; yet neither thermal nor magnetic curves reveal critical points that indicate a differential solution of the globules; thirdly, when high-speed steel is heated to a temperature approaching its melting point there is a distinct coalescence of the embedded particles which structure becomes normal and can only be obliterated by quenching from exceeding high temperatures. This structure is here shown by micrograph No. 16:

This mixture of the globules behaves in exactly the same manner as before they coalesced; that is, it etches similarly and does not affect the critical points; thus if before coalescing the globules had been of different compositions we would expect that after mixing they would either etch differently or affect the critical points; fourth, in tracing the history of the formation of the globules from the ingot we find that in the ingot they represent a single eutectic mixture which will be considered later and is here shown by micrograph No. 17.
This formation by working begins to break up thusly:

and by further working in the same direction will become elongated into stringers as shown by micrograph No. 19:
and finally by upsetting or by further reduction take the characteristic distribution as shown here by micrograph No. 20:

If then the globules were of different composition there seems to be no place in the history of the steel that allow for their formation.

Professor J. C. Arnold isolated and analyzed a number of tungstide residues from high-speed steel of varying analyses. His results are quite interesting and here is given one analysis of a high-speed steel he used and the analysis of the residue obtained:

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>W</th>
<th>V</th>
<th>Cr</th>
<th>P</th>
<th>S</th>
<th>Im</th>
</tr>
</thead>
<tbody>
<tr>
<td>.56</td>
<td>.34</td>
<td>.058</td>
<td>.017</td>
<td>0.20</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

St. steel dissolved Grams

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>W</th>
<th>V</th>
<th>Cr</th>
<th>P</th>
<th>S</th>
<th>Im</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.7718</td>
<td>2.0144</td>
<td>2.32</td>
<td>23.96</td>
<td>3.15</td>
<td>.08424</td>
<td>4.86</td>
<td></td>
</tr>
<tr>
<td>3.9466</td>
<td>2.0426</td>
<td>2.32</td>
<td>23.62</td>
<td>3.15</td>
<td>.08424</td>
<td>4.81</td>
<td></td>
</tr>
</tbody>
</table>

It will be noticed from the above analysis that a proportionally greater percentage of the tungsten is contained in the residue obtained. Thus it would be expected that an increase in the tungsten content would increase the quantity of the globules and this has been confirmed by an examination of a number of high-speed steels containing tungsten in varying percentages. Also we have found as did Honda and Murakami that an increase in the percentage of carbon or chromium with the tungsten content remaining the same did not noticeably increase the quantity of the globules. We have also etched a number of specimens of ferro-tungsten containing less than .20 carbon and from 65% to 80% tungsten and found that the sodium-peroxide and ferricyanide reagents react on it much in the same manner as upon the globules of high-speed steel. Thus in view of the evidence presented we believe we are justified in stating that the embedded
globules in high-speed steel are of a complex but similar chemical composition and should be designated as tungstides instead of carbides even though they are not pure tungstides.
The structure of the ingot lends an interesting aspect to the constitution of high-speed steel. Here is shown micrograph No. 21 of the ingot as cast taken at 200 diameters magnification:

200 X

The part of the ingot indicated by the letter "A" probably solidified first giving rise to a eutectic mixture represented by the letter "B". But at the same time this eutectic is solidifying areas of the molten solution entrapped by the first solidification precipitates the same eutectic (marked "C" on the micrograph), since the solution by partly solidifying enriches the remainder in those elements that will produce the lowest melting mixture.

Upon annealing the ingot only two constituents are noticeable as shown by micrograph No. 22. Then by etching the specimen with H₂O₂ NaOH we get a structure represented by micrograph No. 23:
The eutectic marked "B" corresponds to that marked "B" in micrograph No. 21, and the eutectic marked "C" likewise corresponds to that marked "C". Thus from evidence presented elsewhere in this paper these two constituents are the same differing only in quantity as one has been precipitated from a mixture richer in the eutectic than the other. Thus the embedded tungstides in high-speed steel must represent a eutectic mixture and as the eutectic changes with a change in the composition of the steel, the tungstides do not represent a composition of a constant chemical formula.

While studying the structure of the ingot it is interesting to note the structures developed in high-speed steel by hardening from a temperature at which an actual fusion of the tungstide takes place.

In micrograph No. 24 the structure is comparable to the structure of the ingot as cast where there exists a large skeleton of the eutectic and an area of the eutectic having a more granular appearance. By etching the specimen from which this micrograph was made with \((\text{NaOH}) - \text{H}_2\text{O}_2\) we get a structure shown here by micrograph No. 25. That the skeleton of the eutectic of tungstides here represented is a fusion of the tungstides is evidenced by micrograph Nos. 26 and 27 taken along the bar, one end of which was held at room temperature while the other was melted.
A coalescing of the tungstides is very pronounced.

The black areas represented in micrograph No. 28 we believe were one time named "the brittle constituent" by a well-known English Metallurgist and have been at other times called troostite, and only recently a similar micrograph was used by a well-known authority to represent correctly hardened high-speed steel. These black areas however are the same as those shown in micrograph No. 24, and represent a fusion. In proof of this and also in proof that the areas are not troostite, the specimen from which this micrograph was made was annealed and the micrograph No. 29 represents the result:

Notice that the small faint areas of the tungstide are the same as the black areas in micrograph No. 28, and compare with the granular areas shown in micrograph No. 24 showing that a eutectic has resulted from an incipient fusion.
From analyses of tungstide residues of high-speed steel as given by Prof. Arnold, to one of which reference was previously made, it was noted that the proportionally larger percentage of the chromium existing in high-speed steel was to be found in the matrix. This is supported by micrographs Nos. 30 and 31 of steel containing .30 carbon and 11.95 chromium, and .51 carbon and 16.90 chromium, in which no carbides of chromium can be distinguished, and which have the appearance of a perfect solution of the chromium in the iron:

Likewise, from the analysis of the tungstide residues it is apparent that a proportionally larger percentage of the tungsten is contained in the tungstides, and in a tungsten steel of some .70 carbon there exists a large number of embedded globules as would be expected but not near the proportion of these globules will go into solution at high temperatures as the tungstides in high-speed steel indicating that iron dissolving chromium has a greater power to dissolve the tungstides than iron alone.
The distribution of tungstides in high-speed steel is of great importance as a poor distribution gives rise usually to a noticeably inferior steel. The following two micrographs, Nos. 32 and 33, are taken from the same ingot, one taken 1/6 of an inch from the outside and the other 2 1/4 inches from the outside. The magnification of both are the same.

The distribution of the eutectic mixture or of the tungstides is evident as it existed in this ingot. The finer cellular structure is of course the result of the quicker freezing of the outside of the ingot, and as the ingot solidified progressively toward the center, the cellular structure grows coarser in about the same ratio as the rate of solidification of the ingot. Therefore, the correctly cast smaller ingot by solidifying more rapidly than the larger ingot has a more uniform and finer cellular structure. Moreover, obviously the ingot cast at a lower temperature will have a better cellular structure than an ingot cast at a higher temperature. Thus the size of the ingot and the casting temperature by determining the distribution of the eutectic mixture determine partly the distribution of the tungstides in the finished product. Following are two micrographs, nos. 34 and 35, taken longitudinal of two 3/4" square bars rolled from different portions of the ingot. The one on the left was rolled from a 1/2" square
cut from the outside of a 7" ingot, while the one on the right was rolled from a 1½" square cut from the center of the same ingot:

Both bars received the same kind and amount of work yet the tungstide distribution in the bar cut from the outside of the ingot where the cellular structure was finer is far superior to that cut from the inside of the ingot where the cellular was so much coarser. This distribution is further determined by the amount and manner of reduction given the ingot and billet, and here are shown a number of micrographs taken of the longitudinal section that clearly show the result of the amount of work given an ingot. No. 36, billet from a 7" ingot. No. 37, 3-1/8" round rolled from a 4" billet from a 7" ingot. No. 38, 2-3/4" round from a 4" billet from a 6" ingot. No. 39 1½" round from a 2½" billet, from a 4" billet, from a 6" ingot. No. 40, 2/4" round from 2½" billet, from a 2½" billet from a 6" ingot.
In micrograph No. 30 a perfect distribution has been obtained by working the steel in the same direction, but as this came from a 6" ingot the reduction has been very great. If then a good distribution of the tungstides cannot be obtained by ordinary reduction, the manner of reduction must be changed and here is micrograph No. 41 showing a splendid distribution of the tungstides obtained in a block 9-1/4"x6"x1-1/2" thick by upsetting. The micrograph is taken in the direction of the longitudinal section of the bar from which the block was cut and upset.
A good distribution may be obtained by working the steel in the same direction but in and out as illustrated by diagram No. 5 of rolling drill section, where several passes through the rolls are made keeping the bar in a shape similar to that represented by the cross-section No. 4 of diagram No. 5:

and here are shown longitudinal micrographs Nos. 42 and 43 of a 1-3/8" drill section rolled according to the diagram:
While following is produced a micrograph of a 1-3/8" round rolled in the ordinary manner. From these micrographs the superiority of the manner of rolling the drill section is evident:

No. 44

275 x

NaOH-H₂O₂
1. The position of the decalescence points in high-speed steel are exceedingly constant while the position of the recasalscence points depend on the temperature from which cooling begins. The upper decalescence point represents the solution of the tungstides while the lower recasalscence point represents their formation. The lower decalescence point and the upper recasalscence point represent respectively the transformation of sorbite into austenite, and austenite into a lower constituent.

2. Secondary hardness represents a natural occurrence and is dependent upon the carbon-chromium-tungsten content as well as the temperature from which cooling begins and the rate of cooling.

3. An alcoholic solution saturated with picric acid was found best for etching annealed specimens, while an alcoholic solution containing from 6% to 8% HNO₃ was best for hardened specimens. A solution of sodium hydroxide and hydrogen peroxide, and a solution of K₂Fe(CN)₆ were found valuable for developing the tungstides. Heat tinting could also be used.

4. The nomenclature of the constituents of carbon steels is applicable to the constituents of high-speed steels.

5. The embedded globules in high-speed steel are of a complex but similar chemical composition, and should be designated as tungstides.

6. The tungstides are of a eutectic composition.

7. Iron-dissolving chromium has a greater power to dissolve the tungstides than iron alone.

8. The distribution of the tungstides depends upon the size of the ingot and the casting temperature as well as the amount and manner of reduction given the steel from the ingot to the finished bar.
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P. 106-9, cost of crucible steel for carbon and high speed tools. P. 118-9, composition of high speed steels charges.

Cobalt High Speed Steel Not a German Discover 1918. [In Iron Age. v. 101, p. 321.]

Discussion and quotation from the ironmonger concerning the relocation of the German patent on cobalt tool steel, as result of decision of British court in the action brought by the Damemora Steel works of Sheffield.

Guillet, L. & H. Godfraind.

Quelques observations sur "L Steelite" 1918. [In Rev. de Métauxurgie, v. 16, p. 389-46, abstr. in Iron Age, v. 102, p. 1584-5.]

Some observation on steelite including comparison made of the variation in hardness at different temperature of steelite and a superior quality of high-speed steel.

How small tools were made quickly. 1918. [In Iron Trade Rev. v. 52, p. 858-9.]

Method for making high-speed steel reamers developed in Jackson, Tenn. shop of Illinois Central Railroad.

The New Cobalt Tool Steel. 1918. [In Iron Age. v. 91, p. 1477.]

Mention of a detailed report of extensive comparative tests of the new German cobalt steel with other tool steels, sent out by the Becker Steel Co. of America.

New High-Speed Tool Steel High in Cobalt. 1918. [In Iron Age, v. 101, p. 743.]

U. S. Pat. 1,223,116 of J. H. Parker and E. H. Delong of New high-speed alloy steel containing 30 percent cobalt, 2 percent vanadium, 3.5% chromium, 12% tungsten, 0.25% carbon.

Oberg, E. & P. D. Jones.

Iron and Steel. 1918. [In N. Y. Industrial Press, 328 pp.]

P. 276-97, High Speed Steel, includes origin, Taylor-White process of heat treatment production of high speed steel, effect of different elements in high speed steels, hardening practice, tempering, annealing, uses.

1918—Okochi, K., Kanima, K., Sato, N.


Experimental determination of modulus of elasticity, modulus of rigidity, Brinell hardness number, thermal dilation, thermal conductivity, and magnetization at high temperatures of specimens of gun steel, nickel steel, nickel-molybdenum steel and tungsten steel.
The Salvaging of High Speed Steel. 1918. (In Iron Trade Rev. v. 62, p. 845-8.)

Practical methods for conserving this valuable material, re-smelting, building up tools, electric butt-welding tools.

Yatesevitch, M. Translated by H. Herbert. 

Research on high-speed steel made at the laboratory at Harvard. Study on the "Dreadnaught" steel of the Halcomb Steel Co., on determination of the modifications in structure and caused by being heated and cooling under various conditions, microscopic study of heat-treatment, relation between hardness and heat treatment.

1919---Andrew, J. H. & G. W. Green.

Practical application of scientific methods to high-speed steel practice, following through the steel from the state of ingot to the finished tool.

Arnold, J. W. & P. Ibbotson.
The Molecular Constitutions of High-Speed Tool Steels and Their Correlations with Lathe Efficiencies. 1919. (In Jnl. of Iron & Steel Institute v. 99, p. 407-26, disc. p. 429-35, 2 plates, 1 insert; abstr. in Iron Trade Rev. v. 64, p. 1419 to 1421.)

The Chemical constitution of high-speed steels, correlation of the chemical and microscopic analyses with lathe efficiencies of the series. Note on surface tension effects in high-speed steels by F. C. Thompson.

Gullover, G. H.

Hibbard, H. D.

Hoffman, R. B.
Favorable Results from Cobalt. 1919. (In Amer. Soc. Test. Mat. v. 19, p. 177-179; iron Age, v. 104, p. 21-2.)

Discussion of Dr. Mathew's paper. Analyses and tests of high-speed steel containing cobalt.

Horvitz, S. J.

Composition, curriculae and electric processes of manufacture, hardening, heat treatment, theory of hardening, physical properties. 13 microphotographs.

Johnson, J. E.

A cast tool steel claimed to have the properties of a high speed steel.

Matthews, J. A.

Evolution from air-hardening steel, effects of chromium and tungsten, detection of overheating, recent disc of vanadium.

Parker, J. H.
High cobalt content and high drawing temperatures. 1919. (In Amer. Soc. Test. Mat. v. 15, p. 159-61; Iron Age, v. 104, p. 101.)

Discussion of Dr. Mathew's paper, concerning use of vanadium and cobalt and of the value of chemical analyses.

Poliakoff, K.
1919--Poliakov, E.
Specifications for High-Speed Steels, 1919. (In Iron Age, v. 103, p. 827-9.)
Summarizes opinions of four European manufacturers on thirteen requirements to be considered in working out specifications for delivery, dealing especially with the test tools.

Netter, E.W.
Table of limits and desired analysis resulting from study of high speed steel analyses.

1919--Seidell, L. R. and G. J. Harwitz.
Physical properties of high chrome steel. 1919, (In Iron Age, v. 103, p. 291-4.)
Relation between hardness and double carbides in solutions, maximum tensile strength and ductility.

Use of Prof. J. O. Arnold of 6% molybdenum for 19% tungsten in high speed steel with one fourth % vanadium as a molybdenum stabilizer.

1920--Arnold, J. O.
The Properties of Water Quenched Vanadium-molybdenum High-speed steel. 1920. [In Engr. v. 128, p. 480]
Properties of a high-speed steel, patented under a sealed patent in September 1919, substituted for tungsten, molybdenum associated with a little over 1% of vanadium, the key element of the chemical composition. The vanadium appears to stabilize the variable properties of molybdenum steel, and to prevent cracking during the waterhardening operation.

Honda, K. & T. Murakami.
On the structural constitution of high speed steel containing chromium and tungsten and the effect of these elements on its hardening and tempering. 1920. (In Science Report of the Tohoku Imperial University, v. 9, p. 143-68; 7 plates; Jnl. Iron & Steel Inst. Reprint 16.)
Object of research is to ascertain the structural constitution of high-speed steel, the change of these constituents during heating and cooling, and the effect of these constituents upon hardening and tempering.

Hope, J. A.
Construction of remelting furnaces, crucible, molds, drawing out of ingots procedure in melting; costs.

Hunter, J. V.
Making Forged High-Speed Twist Drills. 1920. (In Amer. Mach. v. 52, p. 719-22.)
Methods used by Kettler, Elliot Erection Co., Chicago.

Langhamer, A. J.
P. 669, Current sales practices, general review of tool steel, high-speed steel, molybdenum, influence of chemical composition, insincerely of recommended heat treatments, table of maker's recommendations for treating lathes and plant tools. P. 959, Conditions entering into the testing of a tool for cutting as listed by Taylor and discussed, method of eliminating most of the variables from a comparative test for the efficiency of several brands of commercial tool steel, p. 959. Detailed description of tests on 16 high speed steels, with data as to performance, chemical composition, heat-treatment and hardness.

1920--MacFarlan, A. F.
High Speed Steel Drop Forgings for Killing Cutters and Special Tools. 1920. 34
(In Jnl. Amer. Steel Treaters Soc. v. 2, p. 798-97.)
Advantages claimed for drop-forged high speed tool blanks are more homogeneous structure, lower machine cost, lower scrap losses, time saved in making a tool, elimination of physical defects, and increased production per tool.
1920—McKenna, R. O.


Details of charging, melting, slagging, teeming, forging heat treatment are discussed and the various important points in the electric furnace practice given.

Tool Steels Influence on Progress and Prosperity 1920. (In Raw Material v. 2, p. 54-59.)

Describes alloy steels intermediate between carbon and high speed steels.

Aitchison, L.

The New High Speed Steel. 1920. (In Autocar. v. 44, p. 56-7.)

History of high speed steel, new formula using molybdenum of Prof. Arnold, costs.
HEAT-TREATMENT OF HIGH-SPEED STEEL.

1900—Steel for High-Speed cutting tools. 1900. (In Mach. Engr., v. 6, p. 688-5.)
Editorial concerning the patent specifications of the Taylor-White process.

Reprint of the British patent 10756 of 1900.

1903—King, C. T.
Development of tool steel, discovery of high-speed steel, cause of change in steel structure by heat treatment.

Rushmer, H. W.
High Speed Steel. 1903. (In Iron Trade Rev. v. 56, p. 50-1, Sept. 24, Amer. Mach., v. 26, p. 1270-61.)
Discovery of Taylor-White process, superiority of new steels, annealing, forging and tempering high-speed steels.

Spuller, J.
Zur Kenntnis der Theorie der sogensamten Rapid- und Naturhartern Stahle. 1903. (In Chem. Zeitung., v. 27, p. 158-6-6.)
On the knowledge of the theory of the rapid and self-hardening steels considering that as the carbon of the iron carbide becomes mobile at about 1000° C it passes out of the iron carbide and forms chrome carbide, tungsten carbide, it playing a most important part in imparting hardness to the steel.


1904—Brown, W.
High-Speed Tool Steels. 1904. (In Amer. Mach., v. 27, p. 73706.)
Heat treatment of hardening of tools; rate of speed desirable.

Bokardt, H.
Contribution to the knowledge and theory of high-speed steels. Discussion of the properties of the Taylor-White and European steels made after the Taylor-White process. Deals especially with the cutting and high-speed qualities.

Gedhill, H. M.
History, composition, effect of combination of iron and carbide with tungsten and chromium, with tungsten, with molybdenum and chromium, molybdenum and tungsten and chromium; influence of each; analyses; heat-treatment, results of tests. 7 plates.

Gedhill, J. M.
Paper read before the Coventry Engr. Soc. Mar. 4, 1904. Manufacture of crucible steel, process of converting crucible steel into high-speed steel, annealing, forging and hardening the tools, heat treatment of high-speed steel, cutting tests.
1904--High-Speed Tool Steels. 1904. (In Mach., v. 10, p. 53405.)

Practical suggestions for hardening the new steels.

Osmond, F.


Contribution to the allotropic theory of high-speed steel.

The Practical Handling of High-Speed Steels. 1904. (In Iron Age, v. 74, Oct. 6, p. 7-8.)

Treatment of high speed tools, heating, hardening, quenching in fish oil, drawing, costs.


Detailed tests on chrome vanadium spring steel.

Structure of High-Speed Steels. 1904. (In Engr., v. 98, p. 90.)

Editorial referring to papers of Le Chatelier and Osmond in Bull. Soc. Encouragement pour l'industrie Nationale.

Wesley, P.

High-Speed Steel for Finishing. 1904. (In Amer. Mach., v. 27, p. 529-30.)

Result of experimenting on use of high speed steel tool for finishing. Tool was heated till the point burnt off, and cooled in the air blast.

1905--Carpenter, H. C. H.


Concludes that the hardening of rapid tool steel involves the widening, splitting, or lowering of the critical ranges of the special alloy element, and the complete suppression of the widened, split, or lowered range by a mild quenching.

Garnier, J.

Les aciers a outils a coupe rapide. Preparation et emploi dans les ateliers. 1905. (In Genie Civil, v. 47, p. 103-8.)

Tool steels for high speed. Preparation and use in the shops. Composition influence of the various constituents, preparation and treatment of rapid steels applications, results of use of "A.W." steel.

Grenet, L.


Note on the hardening of steel, p. 987 chrome-tungsten and high-speed steels. Considers that hardening is caused by a transformation in the cooling to a lower temperature and not by the conservation of a stable state formed at a high temperature.

Gaillat, L.


P. 316 definition, history, transformation points of carbon steels; p. 323, theory of the hardening of carbon steels. To harden a carbon tool steel, it is necessary that the hardening temperature be higher, than transformation point A; p. 336 composition of high speed steel, constitution of chromium and of tungsten steels; p. 380-3, transformation points of chrome-tungsten steel a influence of the constituents; p. 363, properties, treatment, results obtained at Manchester and at Birmingham.


Bradshaw furnace for use in hardening steel. Fig. 4, heating and cooling curve of Seiboma and Dickstahls H.C. High-speed steel.

Carpenter, H. C. H.

300-4, Stahl u Eisen. v. 26, p. 1018-9, transl. in Metallurgie v. 3, p. 511-22, abstr. Mech. Engr. v. 18, p. 164-70.) Report of research to ascertain whether the temperature at which high-speed steels soften can be pushed higher than 700°C.

Guillet, Leon.
Quaternary Steels. 1906. (In Jnl. Iron and Steel Institute pt. 2, p. 1-141, 1 insert.) Research to systematize the use of quaternary steels, or an alloy or iron, carbon and two other added elements.

Process of Hardening High-Speed Steel. 1906. (In Mech. Engr. v. 17, p. 504.) Patented process of S.H. Brayshaw, heating the steel up to a very high temperature, soaking it in a high temperature bath from 900° to 950° C, quenching it in a bath at 100° C.

Thallmer, C.
Die Entwicklung des Schmalarbeitsstahles in Deutschland. 1906. (In Zeit. des Verein deut. Ing. v. 50, p. 1690-7, 1 insert.) The development of high-speed steel in Germany. The introduction of the Taylor-White process, outline of process, chemical composition of high-speed steel influence of carbon, chromium tungsten, molybdenum, silicon; new knowledge on the relation between chemical composition and the hardening effect the high-speed steels in use.

1907—Anshy, G.

Becker, C. M.
The Making of High-Speed Steel Tools, 1907. (In Amer. Mach. 30 pt. 1, p. 441.) Discusses forging, kind of furnace, heating for hardening, the oil bath, method of dipping, degree of hardness desired, tempering furnace.

Carpenter, H. C. W.
High Speed Tool Steel. 1907. (In Iron Age, v. 79; p. 622-4.) Contribution to the discussion of S. W. Taylor's "On the Art of Cutting Metals" and reprinted from the proceedings of the ASME. Includes corrections red hardness, structure of steel, the heat at which tools cut best, other hardening agents than carbon, the action of chromium and tungsten, classification of types cutting tools, and the question of maximum temperature.

Guillet, L.

Lindsay, G.

Scott, C. W.
Annealing and Hardening High-Speed Steel. 1907. (In Amer. Mach. v. 30, pt. 1, p. 322-4.) Recommends annealing in cast iron box, heating to 800° C for at least 5 hrs., raise heat to 900° C, shut off fire, close door, remove steel after 12 hrs.

Scott, C. W.
Annealing High-Speed Steel. 1907. (In Amer. Mach. v. 30, pt. 2, p. 493.) Five different methods which can be used for annealing high-speed steel attempt to disprove statements of Mr. Viall.

Scott, C. W.
Furnaces for tempering high-speed steel. 1907. (In Amer. Mach. v. 30, pt 1, p. 664-5.) Suggests furnaces most appropriate for small, and larger tools, and for all round work.
Steele, J.
Hardening and Tempering High-Speed Steel. 1907. (In Amer. Mach. v. 30, pt. 2, p. 562-4.)
Practical discussion of treatment of high-speed steel tool, use of a forge, advice users not to temper high-speed steel, rehardening steel.

S. L. W.
High-Speed Steel. Some Experiences in Annealing Machining and Hardening 1907. (In Amer. Mach. v. 30, pt. 1, p. 61.)
Practical experience of man unfamiliar with methods of treating high-speed steel.

Taylor, F. W.
F. 22-54. Modern high speed tools using high-speed steel, chemical composition of tool steels for high speed, discovery of high speed, discovery of high-speed steel, Amer. Mach. extracts those parts of practical shop values.

1908--Becker, O. W.
Charging of crucible, melting hole, heating and pouring of the melt, molding the ingot, annealing costs.

Carpenter, H. U. H.
Composition, manufacture, heat treatment of high-speed tools manufacture of tool steel in electric furnace, welding high-speed to mild steel, summarizes possible improvements in manufacture and composition of high-speed steel.

Fabrication et usage des outils en acier a grande vitesse. 1908. (In Rev. Industrielle, p. 34660, 361-2.)
Manufacture and use of tools of high-speed steel. Discussion of paper by A. L. Valentine in the Amer. Mach. includes composition of high-speed steel, analyses, tools used in tests, factors which influence the cutting speed, economic results, hardening high-speed steel, determination of the temperature uses of high-speed steel, and economics which results from its use.

Gross, H.
Hardening High-Speed Steels. 1908. (In Iron Age, v. 61, p. 147; Mech. Engr. v. 22, p. 57-8.)
Rules to follow in heating and quenching high-speed steels, the necessity of proper hardening.

High Speed Tool Hardening Furnaces. 1908. (In Mech. Engr. v. 21, p. 414-5, 520.)
Illustrated description of Brayshaw's patent salt-bath for hardening and patent furnace for high-speed steel.

Hill, H. H.
Paper read before the Liverpool Engng. Soc. Deals with the heat treatment or the annealing, hardening and tempering, grinding, finishing.

Brief illustrated description of high-speed steel tool heating furnace of the British Gas Furnace & Tool Co.

Osborn, F. M.
Tool Steel, 1908. (In Iron Age, v. 82, p. 1812-3.)
Abstract of pamphlet, a reprint of a paper before the Leeds Ass'n of Engrs. Heat treatment after forging and grinding, results in turning tires at the New York Central shops, making of twist drills and milling cutters from high-speed steel.
1908--A Plant for Hardening High-Speed Steels. 1908. (In Iron Age, v. 82, p. 1216-7.)
Crucible gas furnace for the barium chloride bath, preheating furnace, an oil tempering furnace and quenching baths in the plant of Wheelock, Lovejoy & Co. New York.

Robini
La Dureté du Chaud des Aciers. 1908. (in Rev. de Met. Mem. v. 16, p. 893-906.)
The hardness of steels when hot.
P. 906-8. Study of high speed steels, cooling curves.

Taylor, F. W. and A. Wallis, translation.
Translation of "On the Art of Cutting Metals" reviewed in Zeit. des Ver. deut. Ing. v. 32, p. 970.

Valentine, A. L.
Composition of metal, forging, grinding and tempering of lathe tools and milling cutters.

Vialli, E.
The Treatment of High-Speed Steel. 1908. (In Amer. Mach. v. 31, p. 314-6.)
Treatment for Bohler's Syran, Bohler's-Boreas, Jessop's Ark, Bethlehem self-hardening, Crescent self-hardening, Midvale special, Firth-Sterling Blue chip, Allen's high-speed and Burgess' No. 5 special.

Becker, C. H.
Annealing High-Speed Steel. 1908. (In Amer. Mach. v. 32, p. 660-1, pt. 1.)
Furnace, quick and slow annealing, appliances for slow cooling, annealing, temperatures, metal colors left by annealing and electrical annealing.

1909--Becker, C. H.
Annealing High-Speed Steel. 1909. (In Amer. Mach. v. 32, p. 660-1.)
Furnace, quick and slow annealing, appliances for slow cooling, annealing, temperatures, colors left by annealing and electrical annealing.

Clarage, E. T.
Explanation of the hardening of carbon steels, of high speed steels, and discussion of the progress made by American manufacturers over that of English.

Groocock, W. C.
Annealing by placing tool in a gas furnace at night raise it to 1400-1600° let it cool down in the furnace, and take it out about 10 o'clock the following morning, cool enough to handle, and soft enough to cut.

The Newer British High-Speed Steels. 1909. (In Amer. Mach. v. 32, pt. 1, p. 586-7.)
Directions given by Samuel Osborn & Co. Ltd., for hardening lathe and planer tools, data as to endurance under cut from tests of J. J. Saville & Co., Ltd., Thomas Nash & Sons, and Spear & Jacksons, Ltd.

A New Steel. 1909. (In Engng. v. 56, p. 190; Amer. Mach. v. 32, pt. 1, p. 337.)
New High Speed Steel which is hardened in water or Jonas and Culver of the Continental Steel Works, Experiments leading up to discovery.

Some tests of a New High Speed Steel. 1909. (In Amer. Mach. v. 32, p. 847-50, pt.1.)
Novo Superior steel in turning and drilling tests working on forged, rolled, and cast steel and cast iron. Rules for forging, hardening and grinding.

1910--Carter, W.
Becker, O. M.
The development, nature, treatment and use of high-speed steels. Problems
involved in the use of high speed tools, analyses of high speed and special steels,
reference tables for determining cutting speeds.

Brandt, W. V.
High-Speed Tool Steel. 1910. (In Iron Age, v. 66, p. 1045; Mach. Engr. v. 27,
p. 28.)

A High-Speed Steel Tempering Furnace. 1910. (In Engr. v. 107, p. 162.)
Two Chamber gas furnace constructed by Churchill Machine Tool Co. of Manchester,
England.

Smith, W. G.
537-60.)
Abstract of article in "The Armour Eng." history of high-speed steel, in-
fluence of carbon, chromium, tungsten, molybdenum, silicon, method of forging,
tempering, the barium chloride process, and quenching.

Hardening of tools of high speed steel; Refers to methods mentioned in Amer.
Machinist.

1911--Berg, C. P.
15, p. 728-64, Mach Engr. v. 27, p. 184-8.)
Relation between temperature and life of tools. Experiments to establish a
rule as to how rapidly the steel should be heated under the high heat treatment
by a heat absorption test, to determine at which degree of temperature in the heat-
treatment, the maximum cutting efficiency occurs for a steel of a certain chemical
composition, to give the reasons for the relation found by the test, and to
illustrate the same by photo-micrographs.

Cleghorn, J. M.
762-6.)
Composition, role of different metals, melting, annealing, forging, and
hardening, grinding, uses of high-speed steels.

Grenet, L.
Tremp, Recuit, Cementation et conditions d’emploi des Aciers. 1911. Paris
Beranger 429 pp.
Tempering, annealing, case-hardening.
P. 346-461. Special steels, including high speed; properties, forging, heat
treatment.

Jones, E. H.
P 61-6. Heat-treatment of high-speed steel, p. 66-76 treatment of Bushet,
"Novo", "Ultissileum", "Blue-chip" high speed steels.

1912--Annealing High-Speed Steel, 1912. (In Machy. v. 19, p. 257.)
Pocket in air-slaked lime, heated in an annealing oven to 1900° to 50° F
for 9/10 hours, or packed directly in the oven, heat to 1700° 50° F for two hrs.

Emous, J. V.
284-6; Iron Trade Rev, v. 50, p. 450-2, one plate.)
Gives heat treatment for both carbon or tool steel and high speed steel.

Herbert, E. C.
The Influence of Heat on Hardened Tool Steels. 1912. (In Jul. Iron and Steel
Inst. v. 66, p. 586-78; Engng. v. 55, p. 451-7; disc. in Engr. v. 112, p. 364-5;
Refers especially to the heat generated in the cutting operation. Gives break-
ing tests, with resulting hardness, toughness and durability temperatures curves
for two high-speed steel.
Annealing High-Speed Steel in a Blacksmith's Forge for Hardening. 1912.
In Machinery, v. 18, p. 864-5.)
Coating of work with coating of fire clay and salt, and a thin shield of sheet metal, and then using coal forge fire for heating.

1913--Annealing High-Speed Steel. 1913. (In Machinery, v. 19, p. 451.)
Methods given in Machinery, v. 19, p. 276, disputed, and gives method with annealing chart used by one of the largest high-speed tool steel manufacturers in America.

Armstrong, G. S.

Bigger, G. M.
Tool Steel from a Salesman's Point of View. 1915. (In Iron Age, v. 91, p. 708-9; Mech. Eng. v. 31, p. 280-2.)
F. 707-8. high speed steel composition and annealing and the influence of vanadium on the cutting speed and durability.

DeNolly
Structure des aciers et modifications accompagnant les traitements thermique 1915. (In Bull. Soc. l'Ind. Min. v. 4, p. 271-86. 8 plates.)
Exposé Structure of steels and modifications accompanying the heat treatment. Point of transformation, theory of hardening, use of microscope, dilation curves of a high speed steel, heated to 850° 1050° C.

1914--Denis, M.
Aciers a outils. 1914. (In Rev. de Met. Mem. v. 11, 4-94.)
Tool steels. The cutting properties of tool steels following their heat treatment, and the practical utilization of these cutting properties.

Denis.
Investigation into the general properties of tool steel, discussing the method of tests and heat treatment of various kinds of tool steels, detailed data of the tests, and conclusions from this data.

DeNolly, H. & L. Veyret.
Note on the Transformations of Steels. 1914. (In Jnl. Iron and Steel Inst v. 90, p. 166-80; Engng. v. 95, p. 631-2.)
Discussion of the carbide theory, the allotripic theory, and a theory of the dissociation of the carbide accompanied by the solid solution in the iron, of the carbon liberated by the association, proposed by the authors, and illustrated by curves of critical points of high-speed tool steel.


Portevin, A.
Influence of the time of reheating after the hardening on the results of this process.

1915--Abbott, R.R.
Changes in structure of carbon and alloy steels, including tool steels by heat treatment.

Edwards, C. A. & H. Kikawa.


Hibbard, H. D.

P. 55-57. High Speed Steels including manufacture, composition, effect of carbon, chromium, tungsten, molybdenum, cobalt, copper, sulphur and phosphorus in high speed steel, heat-treatment, theory patents and bibliography.

Lantsberry, F. C. A. H.

Heat-treatment, theory of hardness, microstructure.

Millholland, R. A.

Removal of decarburized area to secure a good cutting edge.


P. 181-210. High speed steel includes melting difficulties, forging, carbide, envelopes, milling cutters, clinking, flaking, cracking, annealing, red-hardness, high heat, quenching, lathe tests, over-heating, tempering, testing, blistering, grinding.


Shows by a discussion of a long series of experiments how sensitive one particular chromium steel is, to very slight variations in treatment.

German High Speed Steel. 1916. (In Iron Age, v. 98, p. 1111, quotations from Elektro-technische Rundschau.)

Composition of high speed steel for lathe tools, brief outline of hardening process.


Directions distributed by the Vanadium-Alloys Steel Co., Pittsburgh.

Honda, K., K. Tawara and H. Takagi.
The Transformations of Special Steels at High Temperature 1915. (In Jnl. Iron & Steel Inst. v. 95, p.224-54, 5 plates.)

Sauveur, A.

P. 145-55. Chrome-tungsten or high-speed steel microphotographs, critical points, heating and cooling curves, etching.


Abstract of interim report of the Tool Steel Research Committee of tests on ordinary high-speed steel.
1917—Bellis, A. E. & T. W. Hardy.

Discussion, tables, plates of microphotographs of hardening experiments on five different high-speed tools.

Forshaw, A.
Gas Furnaces, their design, and manipulation. 1917. (In Engng. v. 104, p. 535-37, 158-91.)

P. 491, furnaces used in the hardening of high-speed steel, give chamber furnace, tools are placed in preheater and heated to redness, then transferred to hot chamber, heated to between 1200°-1300° C, then quenched in oil, or in "Fenaust" at a temperature of 250° C.

1917—Koroff, F. H.
Hardening High-Speed Steel Tools. 1917. (In Amer. Mach. v. 46, p. 576.)

Cyanide process for hardening steel tools with delicate edges.

Thompson, J.
Hardening High-Speed Steel. 1917. (In Amer. Mach. v. 46, p. 244.)

Instruction for hardening of high speed steel cutters of tools of irregular shape and great accuracy.

1908—Arnold, J. U.

Description of pyrometers in use at Sheffield University, where high-speed steel is generally hardened from a temperature of 1200° C, in a bath of maximum barium chloride fused by the aid of iron electrodes.

Bullens, D. E.

Edwards, U. A.

Hardening and tempering of nickel, chromium, tungsten and high-speed chromium tungsten steels.

High-Speed Steel Hardening Furnace. 1918. (In Eng. v. 116, p. 319.)

Brief description and illustration of furnace introduced by Brayshaw Furnaces Tools Ltd., Manchester.

Obert, E. & E. L. Jones.
Iron and Steel. 1918. (In N. Y. Industrial Press, 328 pp.)
P. 276-97, High Speed Steel, includes origin, Taylor-White process of heat-treatment, production of high speed steel, effect of different elements of high speed steels, hardening practice, tempering, annealing, uses.

Thorne, J. L.
How to treat high-speed steel. 1918. (In Iron Age, v. 102, p. 314.)

Abstract of paper on the metallurgical treatment of high speed steel before the Steel Treating Research Sec. of Detroit.

1918—Yatesevitch, H. Translated by M. Herbert.

Research on high speed steel made at the Laboratory at Harvard. Study on the "Dreadnought" steel of the Falcon Steel Company. On determination of the modifications in structure and caused by heating and cooling under various conditions, microscopic study of heat-treatment, relation between hardness and heat-treatment.
1919--A special Tool Steel Heating Furnace. 1918. (In Iron Age, v. 101, p. 553.)
Furnace for use with tool of high speed steel, patented by W. E. Bennett, of
the Bennett Metal Company Treating Company, Hinswood, Vt.

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