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The Properties and Heat Treatment of High Speed Steel
THE PROPERTIES AND HEAT TREATMENT OF HIGH SPEED STEEL

BY

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THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

HENRY ERNEST BRAUER

ENTITLED: THE PROPERTIES AND HEAT TREATMENT OF HIGH SPEED STEELS

IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE DEGREE OF BACHELOR OF SCIENCE IN CHEMICAL ENGINEERING

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ACKNOWLEDGMENT

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THE PROPERTIES AND HEAT TREATMENT OF HIGH SPEED STEEL

I INTRODUCTION

1. The Purpose of the Investigation

The study of the heat treatment of high speed steels is a popular subject among metallurgists in these days, but the majority of the articles published in the current scientific magazines are nevertheless extremely vague. Claims are made which cannot be substantiated and heat treatment rules are given which are not at all general. The theory of the normal carbon steels is extremely simple because these steels pass from one structure into the next at definite temperatures, and all thermal changes are definite. The Roberts Austin Roozeboom Equilibrium Diagram of the Iron Carbon Series covers all cases of carbon steels. High speed steels, however, are far more complex, because a study of them involves the investigation of the formation of chemical compounds and a great variation of thermal changes.

This work was undertaken to make a short general study of some of the leading high speed steels on the market. A special study was made: (1) of the position and intensity of critical points and their relation to the heat treatment (2) of the temperature and methods of heat treatment (3) of the microstructure and hardness after all heat treatments.

2. The Present Status of the Field

A large amount of work has been done in this direction in the last decade. The heat treatment of steels in general has become
so extensive that a magazine, "The Journal of the American Steel Treaters Society" is now being published monthly.

Alloy steels were manufactured as early as 1895, and at present, manganese, chromium, molybdenum, tungsten, nickel, vanadium and cobalt are used in alloy steels. In high speed steels a combination of several of the above named metals are used to attain the desired red hardness. According to Bullens (1) most high speed steels contain from 15 to 30% tungsten, 3 to 5% chromium, 0.5 to 2% vanadium and 0.6 to 0.8% carbon. Other elements are present only in very small quantities. Cobalt and molybdenum are sometimes used as substitutes for tungsten.

Tungsten is the chief element in most high speed steels. The theory generally accepted today is (1,2) that tungsten combines with iron and carbon to form double carbides of tungsten or that tungstides are formed. Other authorities do not want to commit themselves and call the compound formed simply X compound. Whatever the compound is, that is formed, some of its properties determine the very name "High Speed Steel". The compound formed is not soluble in the steel except at a very high temperature, nearing the melting point (2,3). By sudden quenching from this temperature, the carbide, tungstide or other compound will be forced to remain in solution. After the carbide has once gone into solution, the steel can be reheated to high temperatures (600° C) (3), and it will retain its extreme toughness and hardness. That is the reason why tools made of this steel will retain their hardness even when run at a high speed and this property is termed red hardness.
Bullens (1) states that chromium lowers the critical points and therefore produces a lowering of temperatures at which hardening can be effected. He further states that chromium causes the steels, of which it is a constituent, to withstand sudden strains and shocks. According to Edwards and Kilkawa (4), the presence of chromium increases the intensity of secondary hardening, that is the hardening set up on tempering. In short, chromium increases hardness.

The effect of vanadium is not very well known. According to Langhammer (3) Vanadium increases the hardness or red hardness in cutting tools and also increases the resistance to wear. It has a strong tendency to absorb oxygen and therefore acts as a purifier. Tiemann (5) states that one percent of vanadium in a high speed steel, containing at least 18% tungsten, enables such a steel to be quenched from a white heat in water without cracking or setting up severe stresses. This is true, however, only when the percentage of carbon does not exceed 0.6.

As stated above, carbon is usually present from 0.6 to 0.8%. It should not be less, because in that case it reduces hardness. More than 0.8% carbon is not desirable because the steel cannot be forged and machined (6) above those amounts.

The use of molybdenum (3) as a major constituent is being discontinued more and more. High speed steel with a good proportion of molybdenum is generally characterized by irregular performance. Such steels crack easily in quenching. Molybdenum steel becomes unstable when rehardened. According to Guillet (2): (1) 0.8% molybdenum is sufficient to exclude free ferrite, even
when only 0.45% carbon is present (2) slow cooling of molybdenum steels causes coarse structure and is very detrimental (3) molybdenum is present as an iron molybdenum compound and (4) there is no increase in hardness as molybdenum increases from 1 to 5%. Guillet also states that molybdenum has an effect similar to that of tungsten, but four times as intense.

Cobalt (3) is sometimes used with molybdenum and tungsten, but its effect is not known.

Yatsevitch (2) of the Technical School of Kiev, Russia, has done a good deal of work on critical point determinations and has shown that the intensity and position of critical points differs with the temperature to which the steel is heated and the rate of cooling. According to Yatsevitch, on cooling from 800° C, only one sharply marked evolution of heat occurs at approximately 665° C. On cooling from 850° C, a critical point occurs at 245° C, but is not as intense as the upper one. Upon cooling from 1000° C, an intense point occurs near 370° C, while the upper point has become feeble and covers a wide range. Rapid cooling intensifies the occurrences.

Various and different heat treatments for high speed steels have been advised by men (7, 8, 9, 10, 1, 4, 6). Taylor and White, the originators of high speed steel, prescribe primary hardening at high temperatures, just below the melting point, and a secondary hardening at 620° C. The statement, just below melting, is very vague and differs with the steel. These men also specify double quenching, namely, molten lead and oil.

According to T. M. Hardy, primary hardening should be conduct-
ed between 1170° C and 1370° C and a secondary hardening or tempering is not deemed necessary.

The user of high speed steel usually knows little or nothing about the reasons for the heat treatments prescribed for him by the manufacturer. In many cases he has no idea as to the constitution of the steel. A standard (3) method of heat treatment is essential for uniformity of good results, but mediocre or poor grades of steel do not in general permit high heats and must be treated accordingly. This is one reason why manufacturers do not agree on their methods of treatment of high speed steels. Such a steel, when not properly heat treated, is practically worthless.

3. Outline of the Investigation

Since a study of high speed steels in general was the aim of the author, the following method of attack was used:

1. Cooling and heating curves were taken of five representative steels manufactured by some of the leading tool steel producers.

2. Each steel was heated to from 25° to 50° above each critical point and oil quenched. A microscopic and photographic study was made of each specimen.

3. Each steel was heat treated at successive temperatures above 1050° C and a microscopic and photographic study was made of each specimen.

4. Tempering treatments were studied.

5. Hardness determinations were made on the specimens.
II EXPERIMENTAL

1. General Method of Attack

There are two methods of attack to the heat treatment problem, namely:

1. The purely practical, in which the results are judged by practical methods, determining the properties.

2. The metallographic or physical chemical in which the chemical action and properties of the steel as a whole and of the various constituents determine the method.

The practical method is all right and sufficient where only one high speed steel or carbon steel is used, but in order to study high speed steels in general, as well as other alloy steels, it is necessary to attack any heat treatment problem from the metallographic standpoint.

As stated by Sauveur and determined by Yatsevitch (2), the critical points in steels, their position and intensity have much to do with the method of heat treatment. For this reason, the problem was attacked with the determination of the thermal changes as its basis. Then, with a knowledge of the critical ranges above 1000° C, it was possible to determine the beginning of hardening. Finally, with a knowledge of the proper hardening temperature, the temperature for proper and maximum tempering can be found.

2. Apparatus

(a) Critical point apparatus

For the determination of critical points, the differential method was used. A diagram of the set-up may be found in Figure I.
A  L & N Potentiometer
B  Galvanometer
C  Lead Storage Battery
D  Cold Junction
E  Quartz Tube Insulation
F  Neutral Body, Fireclay
G  Asbestos Insulation
H  Steel
K  Electric Furnace
L  Thermo-couple, Platinum--Platinum Rhodium
M  Double P.D.T. Switch
N  Rough Emf Adjustment
O  Fine Adjustment Bridge
P  Regulation for Standard Cell Emf
S  Standard Cell, Cadmium
The method used involves the use of a neutral body (2) which undergoes no thermal changes whatsoever in the critical range of the steel under investigation. The author used fireclay. The electromotive force set up in the thermocouples by the heat in the bodies is measured by a Leeds and Northrup Precision Thermocouple Potentiometer, No. 46,364. The galvanometer used is of the D'Arseval type and is a Leeds and Northrup instrument. The potentiometer received its counter E.M.F. from a lead storage battery. The potentiometer is built so that a charged lead storage battery gives approximately the maximum voltage that can be regulated by the resistances in the box, and the minimum E.M.F. obtainable from a lead storage battery is approximately the lowest that can be used as a counter E.M.F. source. The author attempted to use one dry cell, but the voltage was too low, then two dry cells in series were tried, but this gave too high an E.M.F., without the use of an extra rheostat in series with the dry cells. The lead storage battery was found to be the most suitable. Since the potentiometer used in these experiments cannot be connected with two galvanometers to be read simultaneously, a difficulty was encountered. This obstacle was overcome by the use of a double throw pole switch, which permitted the readings of the temperature of the neutral body and the steel alternately at equal intervals of time.

(b) Furnaces

For temperatures up to 1300° C, two Hoskins Chromel electric furnaces were employed. The voltage of the furnaces was 20 and 110 respectively, and the amperage 137 and 10 respectively. The
first condition of amperage and voltage was obtained through an open type transformer. At temperatures above 1200°C, a gas heated pot furnace provided with an airblast was employed. A lead quenching bath was also kept molten in a small pot furnace.

(c) Thermocouples

All the thermocouples used were noble metal couples of platinum, platinum rhodium. The temperature indicators used for direct temperature control and for calibration were a Siemens Halske direct reading millivoltmeter and a Leeds and Northrup potentiometer indicator No. 25,925.

(d) Polishing methods and instruments used

All specimens before being microphotographed, were polished on a series of emory wheels on a Wysor Polishing Machine. Each specimen was then polished on 1, 0, 00 and 000 emory paper by hand and finally polishing them on a rouge block.

(e) Photographic apparatus employed

A Leitz micrometallograph with camera attached was available, for microscopic study. All the pictures shown herein were taken with this instrument.

(f) Hardness machine

For hardness determination, the Scleroscope and Brinell Hardness machine were employed. Since both are standard apparatus a description will be unnecessary.

3. Discussion

(a) Seban Kerau - Furnished by Robert K. Greaves and Co.
Analysis:

<table>
<thead>
<tr>
<th>Element</th>
<th>Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0.68%</td>
</tr>
<tr>
<td>Va</td>
<td>1.65%</td>
</tr>
<tr>
<td>P</td>
<td>0.3%</td>
</tr>
<tr>
<td>Wo</td>
<td>18.6%</td>
</tr>
<tr>
<td>Mo</td>
<td>0.35%</td>
</tr>
<tr>
<td>Mn</td>
<td>0.3%</td>
</tr>
<tr>
<td>Cr</td>
<td>3.8%</td>
</tr>
<tr>
<td>S</td>
<td>0.02%</td>
</tr>
<tr>
<td>Si</td>
<td>0.25%</td>
</tr>
</tbody>
</table>

This is a first grade chrome tungsten high speed steel, according to analysis. A very careful study was first of all made of its thermal changes. In order to be able to make a comparison, the cooling curves of all the steels were taken from above 1000° C. A large number of critical point determinations were made of the Seban Kerau Steel and the results checked quite closely. The curve shown is a typical one. As determined, three critical points are indicated. The upper occurs at 735° C, the middle point at 645° C and the lowest point at 468° C. Perhaps the easiest and probably only way to account for the middle point is to account for it because of the rapid cooling. Yatsevitch's results were somewhat similar on rapid cooling. The composition of the steel under consideration checks fairly closely with that given by Yatsevitch. The results also are very similar except that the author's lowest point is a trifle higher than the one found by Yatsevitch.

Heat treatments were made of this steel at 625, 730, 810, 960, 930, 1030, 1060, 1180, 1215 and 1265° C. Finally, the last specimen was tempered at four successive temperatures. Microphotographs were taken of all specimens, the most important of which are shown. All photographs were taken at a magnification of 355 diameters.
DIFFERENTIAL CURVES OF STEELS UNDER INVESTIGATION

TEMPERATURE IN DEGREES C.

TEMPERATURE DIFFERENCE BETWEEN NEUTRAL BODY AND STEEL IN DEGREES C.
Note Figure I, which is a photograph of the annealed structure. The double carbide is well diffused. Figure II shows that quenching from above the lower critical point has caused the carbide to segregate into larger spots. The matrix is clearly sorbitic. Hardness has not changed either. The next sample quenched from 730°C in oil shows almost no change. A close study of Figure IV shows that the beginning of solution of the carbide has begun. Figures V, VI, VII and VIII are to some extent puzzling. That there is some free carbide present is inevitable, but the hardness has become greater. Close observation of the photographs convinces the author that, since the steels were heated slowly to the respective temperatures, the white particles have lost their characteristic shape. Segregation of the matrix surrounding the particles has taken place. This fact is clearly brought out in Figures IX and XII. These show pure austenitic structure and very small regular particles of free double carbide. Due to the fact that we have pure austenite, the hardness has fallen down a trifle. Accurate Brinell hardness determinations were not made on the specimens quenched from high temperatures. Approximations, however, indicate that the steel was harder after drawing at 630°C than it was after the primary hardening. After drawing at 890°C, the toughness of the steel broke down for it cracked before the load of 3000 kilograms had been applied. The point at which the hardness, or better, the toughness, falls off is thus termed the breaking down temperature. In this case, this temperature is somewhere near the upper critical point. Before
Figure 1
Annealed
Etched 5 min. 4% HNO₃
Difused double carbide in pearlitic matrix

Figure 2
Heated at 625°C for 5 minutes
Quenched in oil
Etched 10.5 min. 4% HNO₃
Segregated double carbide in sorbitic matrix
Soloroscope 10 - Brinell 208

Figure 3
Heated 730°C for 5 minutes
Quenched in oil
Etched 10 min. 4% HNO₃
Segregated double carbide in sorbitic matrix
Soloroscope 8.5 - Brinell 208

Figure 4
Preheated - Heated 1060°C 5 min.
Quenched in lead - oil
Etched 6 min. 4% HNO₃
Partial solution of carbide
Soloroscope 12 - Brinell 315
**Figure 5**
Preheated - Heated 1050°C for 15 minutes
Quenched in lead - oil
Etched 5 min. 4% HNO₃
Partial solution of carbide austenitic matrix
Scleroscope 12 - Brinell 325

**Figure 6**
Preheated - Heated 1050°C 25 min.
Quenched in lead - oil
Etched 4 min. 4% HNO₃
Partial solution of carbide segregation of matrix
Scleroscope 12.5 - Brinell 444

**Figure 7**
Heated to 1150°C gas furnace
Quenched in oil
Etched 2 min. 4% HNO₃
Segregation of matrix
Scleroscope 23 - Brinell 444

**Figure 8**
Heated to 1150°C in gas furnace
Quenched in oil
Etched 2 min. 4% HNO₃
Segregation of matrix
Scleroscope 18 - Brinell 302
Figure 9
Heated to 1315°C in gas furnace
Quenched in oil
Etched 3 min. 4% HNO₃
Austenitic structure

Figure 10
Heated to 1365°C in gas furnace
Quenched in air blast - water
Etched 25 min. 4% HNO₃
Austenitic structure
Approx. Brinell 350

Figure 11
Specimen 10 tempered at 425°C for 5 minutes
Quenched in oil
Etched 2.5 min. 4% HNO₃
Austenitic structure
Approx. Brinell 320

Figure 12
Specimen 11 tempered at 620°C for 5 minutes
Quenched in oil
Etched 2.5 min. 4% HNO₃
Austenitic structure
Approx. Brinell 375
going on to the next steel, the author should like to call the
reader's attention to the crystal size in Figures IX to XI.
Attention will again be called to this later on.

(b) Red Cut Cobalt High Speed Steel - Furnished by The
Vanadium Alloys Steel Company

Analysis:

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>C</td>
<td>0.66%</td>
<td>S</td>
</tr>
<tr>
<td>Si</td>
<td>0.06%</td>
<td>Cr</td>
</tr>
<tr>
<td>Mn</td>
<td>0.07%</td>
<td>Wo</td>
</tr>
</tbody>
</table>

The only marked difference in composition between this and
the one discussed previously is the presence of the cobalt. This
steel shows two marked critical points of about equal intensity
when cooled from 1000° C. The upper one occurs at 700° C and
the lower one at 280° C. Notice the marked lowering of the
critical points, especially the lower one. Cobalt evidently has
a greater effect on the points than vanadium or tungsten.

In the case of Red Cut Cobalt, as in the case of the Seban
Kerau, there was no marked difference in structure or hardness
between the annealed sample and the samples quenched at temperatu-
res above each critical point. Hardness suddenly rose and solu-
tion was effected at temperatures above 1100° C. Figures XIV,
 XV and XVI represent specimens which were treated to nearly the
same temperatures, but their structures vary. Specimen XVI has
a matrix of pure martensite, is very brittle and extremely hard.
Likely, this condition is due to slow cooling. The reaction of
transformation had proceeded a trifle too far when cooling was
Figure 13
Heated at 600°C for 5 min.
Quenched in oil
Etched 4 min. 4% HNO₃
Double carbide in pearlitic matrix
Scleroscope 8 - Brinell 208

Figure 14
Heated to 1150°C in gas furnace
Quenched in oil
Etched 2 min. 4% HNO₃
Segregation of matrix
Scleroscope 38 - Brinell 600

Figure 15
Heated to 1180°C gas furnace
Quenched in lead - oil
Etched 6 min. 4% HNO₃
Appearance of austenitic structure
Scleroscope 32 - Brinell 600

Figure 16
Preheated - Heated at 1150°C for 6 minutes
Quenched in oil
Etched 13 min. 4% HNO₃
Martensitic matrix
Scleroscope 23 - Brinell 782
Heated to 1365°C gas furnace
Quenched in air blast - water
Etched 2.5 min. 4% HNO₃
Large austenitic crystals extremely brittle

Specimen 16b tempered at 435°C for five minutes
Quenched in oil
Etched 1.5 min. 4% HNO₃

Specimen 17 tempered at 630°C for 5 minutes
Quenched in oil
Etched 1.5 min. 4% HNO₃

Specimen 18 tempered at 730°C for 5 minutes
Quenched in oil
Etched 1.5 min. 4% HNO₃
effected. That peculiar structure met with in Figure 7 is again present in Figure 14. But another evidence is brought out by Figure 15, which shows an almost pure austenitic structure. The specimen which is referred to by Figure 15 was properly treated. It was preheated to 800° C, then suddenly heated to 1180° C for a short time and then quenched. The specimen of which Figure 14 is a photograph was slowly heated to 1150° C and held there for a long period of time. The matrix, ferrite plus cementite has segregated in this structure.

Studying Figures 16, 17, 18 and 19 you will recall Figures 9, 10 and 11. Specimens 9 and 16, 10 and 17 and 11 and 18 were treated exactly alike respectively. There was only one difference. While trying to quench 9 and 15 simultaneously, the author dropped 15 out of the tongs and this was consequently quenched about 15 seconds later than 9. The result was the large crystal structure in specimen 15. The tempering effect is nevertheless analogous in the Red Cut Cobalt and the Seban Kerau Steels. The primary hardening rendered the Red Cut Cobalt Steel so weak and brittle that it broke under the brinell ball. Notice also the difference in etching time between specimen 16 and 9.

(c) Tungsten High Speed Steel - Furnished by University Foundry

Analysis was not given. A fine cooling curve was obtained with this specimen, the upper one occurring at 700° C and the lower one at 363° C. These results are more closely in accord with Yatsevitch's (2) results.

Specimen 20 shows a very distinct segregation of double
Figure 20
Heated to 715°C
Quenched in lead - oil
Etched 1.5 min. 4% HNO₃
Marked segregation of double carbide

Figure 21
Preheated to 800°C - Heated at 1080°C for 5 minutes
Quenched in lead - oil
Etched 3 min. 4% HNO₃
Partial solution of double carbide

Figure 22
Heated to 1230°C in gas furnace
Quenched in oil
Etched 3.5 min. 4% HNO₃
Perfect austenitic structure
solution of double carbide
carbide as seen in Figure 16. The author obtained his best structure in the treatment of specimen 23. This has all the characteristics of a well treated high speed steel, namely: small crystals, faint crystal boundaries, an austenitic matrix, almost complete solution of double carbide and a good hardness.

(d) Seminole Medium Tool Steel – Furnished by the Ludlum Steel Company

Analysis was not given. Three critical points were found at 435°, 635° and 925° C, respectively. This steel has almost all the properties of a common carbon steel, as shown under the microscope, but the lower critical point is markedly lower than would be expected in an ordinary carbon steel. The author cannot account for this, since the analysis of the steel is not given. The thermal ranges must have been effected by some special element in the steel. Microscopic analysis gives us conclusive evidence that we have no high speed steel to deal with. We have simply the different structures, austenite, martensite, sorbite and pearlite, depending upon the method of quenching and the temperature from which quenching has taken place. Figure 22 shows an unusually distinct austenitic structure.

(e) Como High Speed Steel – Furnished by Darwin Milner Co.

The heating curve was selected because the critical points, which occurred on cooling from above 1000° C were so dim that they could not be detected with the available instrument, even after repeated trials. Only one distinct critical point was found and this occurred at 730° C. Sudden quenching from above 730° C gave pure austenitic structure. Below the critical point
Figure 23
Annealed at 675° C for 4 hrs.
Cooled in furnace
Etched 12 secs. 4% HNO₃
Pearlitic structure
Scleroscope 23.5 - Brinell 320

Figure 24
Heated to 725° C
Quenched in oil
Etched 12 secs. 4% HNO₃
Sorbitic structure
Scleroscope 21 - Brinell 364

Figure 25
Heated to 925° C
Quenched in oil
Etched 12 secs. 4% HNO₃
Fine martensitic structure
Brinell 530

Figure 26
Preheated - Heated at 1130° C for 5 minutes
Quenched in lead - oil
Etched 1.5 min. 4% HNO₃
Austenite and martensite
Scleroscope 19 - Brinell 515
Figure 37
Heated to 1265°C gas furnace
Quenched in oil
Etched 25 min. 4% HNO₃
Pure austenite
Scleroscope 50 – Brinell 340

Figure 38
Specimen 37 tempered at 420°C
for 5 minutes
Quenched in oil
Etched 1 min. 4% HNO₃
Figure 29
Preheated - Heated at 1115°C for 5 minutes
Quenched in lead - oil
Reheated to 800°C
Quenched in oil
Etched 25 secs. 4% HNO₃
Scleroscope 26

Figure 30
Preheated - Heated at 1160°C for 18 minutes
Quenched in lead - oil
Etched 4 min. 4% HNO₃
Austenitic structure
Scleroscope 10

Figure 31
Heated at 1160°C for 5 minutes
Quenched in air blast
Etched 4 min. 4% HNO₃
Non-uniform austenitic structure
Scleroscope 20
martensite and sorbite were obtained. The specimens cracked very badly when quenched in oil. Notice that very few small white particles can be seen on any of the photographs (Figures 37 and 28). Results similar to these probably helped Guillet to conclude that molybdenum formed a compound with iron and did not form a carbide. Another fact which leads the author to believe that Guillet is correct in his conclusion, is the presence of black spots in Figure 28. The etching solution attacked the compound and a carbide is not first attached by any etching solution.

(f) Discussion in General

In any microscopic study of steel, it is necessary to recognize a structure under the microscope as it appears in etching. No etching rules can be laid down for any steel. Hardy says that a high speed steel should be etched sixteen minutes in a 4 percent solution of nitric acid. This is approximately correct for a properly hardened steel, but a microscopic study is made of a high speed steel to study hardening, therefore, this is of no use to the metallographist.

The scleroscope and brinell hardness determinations show values which are proportional as long as austenite is not formed. Although, as is well known and proved by brinell tests, the hardness of austenite is less than that of martensite, the scleroscope shows a hardness in the case of austenite much greater than that of martensite.

Rapid quenching in a liquid was found to give much better uniformity than quenching in an air blast.
HARDNESS CURVES OF STEELS UNDER INVESTIGATION
BRINELL

BRINELL HARDNESS NUMBERS

TEMPERATURE FROM WHICH QUENCHED IN DEGREES C.
200 400 600 800 1000 1200 1400

SEMINOLE MEDIUM TOOL STEEL
COMO
RED CUT COBALT
SEBAN KERNU
III CONCLUSIONS

1. The results of Yatsevitich in regard to thermal data have been confirmed. In one or two cases the results do not check exactly with those of Yatsevitich, but the slight difference in those cases is probably due to the variation in composition.

2. A high speed steel should not be heated any longer than absolutely necessary. Even though a steel may not be burned upon long heating, at a certain temperature segregation is always effected in the matrix and this condition weakens the steel. This is one reason why a steel should be very rapidly heated from about 700° C to the desired hardening temperature.

3. In heat treatment (11) a steel is preheated to prevent warping. Fast and uneven heating up to that temperature results in warping and cracking of the steel.

4. Uniformity of results is very essential in hardening and therefore the selection of quenching agent must be carefully made. In a steel containing at least 1% vanadium, oil is probably the best quenching medium. In a molybdenum steel, lead as an intermediate quenching agent is desirable to prevent cracking. In lead quenching care must be practiced to prevent the steel from floating and thus being air cooled in one spot.

5. The beginning of hardening is not appreciable under 1050° C. Nevertheless the author does not dispute Savaux's conclusion when he states that the upper critical marks the beginning of hardening. Good primary hardening is not attained in most steels until a
temperature of 1250° C is reached.

6. In the hardening treatment, rapid quenching is absolutely necessary: (1) to prevent the formation of large crystals which render the steel brittle and (2) to prevent the formation of a large amount of hard but brittle martensite.
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