AN INVESTIGATION OF SOME SILVER ALLOY STEELS

Thesis by

William O. Wetmore

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ABSTRACT

The object of this research project was to develop an alloy steel containing an appreciable amount of silver and possessing desirable properties. Investigation revealed that the solubility of silver alone in steel was exceedingly small, less than 0.02 per cent. It was necessary, therefore, to develop some means of increasing the solubility of silver in steel. By alloying silver with copper before adding to steel, it was found that 0.3 per cent silver could be alloyed with the steel. An investigation was conducted on some of the properties of the silver copper steels. The results indicate that additions of silver with copper have little effect on the thermal critical temperatures, on some of the mechanical properties, on the corrosion resistance, on the austenitic grain size, and on the microstructure of 0.15 per cent and 0.35 per cent carbon steels.

AN INVESTIGATION OF SOME SILVER ALLOY STEELS

GENERAL INTRODUCTION

This thesis presents the results of research work conducted by the author during the past three years on silver and silver-copper steels. The primary object of the research program is to develop an alloy steel which contains an appreciable amount of silver and also possesses desirable properties. The investigation consists of a study of the solubility of silver in iron and steel and a study of the effect of additions of silver-copper alloys on the thermal critical temperatures, on some of the mechanical properties, on the corrosion resistance, on the austenitic grain size, and on the microstructure of steel.

Since the investigation covers two different iron alloys, it is necessary to divide this thesis into two sections. The first part covers the research work on the silver-iron alloys only; and the second part, the silver-copper steels.

PART I.

SILVER-IRON ALLOYS

Previous Investigations

The effect of additions of silver on the properties of iron and steel has not interested very many investigators. The cause of the neglect of a thorough investigation of these alloys is probably two-fold. First, from an economic standpoint, it might appear that additions of even very small percentages of silver would increase the price of steel greatly, thus preventing its use. Second, the small amount of work which has been done on these alloys indicates that silver is practically insoluble in iron or steel. The review of the literature which follows presents the work which has already been performed on silver-iron alloys, and bears out the statement made above.

The first report which could be found of an investigation of the silver-steel alloys appeared in 1820. The work was done by Michael Faraday and James Stodart at the Royal Institution of London. In the first article concerning their work,[1] the authors revealed that fibers of pure silver were evident in the structure of the final alloy if the silver content exceeded 0.2 per cent. However, tests conducted by them revealed that this small addition of silver produced a steel of superior quality. The concluding paragraph of this article perhaps expresses their enthusiasm for the silver steel alloys:

"From the facility of obtaining silver, it is probable that its alloys with steel is the most valuable of those we have made. To enumerate its application, would be to name almost every edge tool. It is probable that it will prove valuable for making dies, especially when combined with the best Indian steel. Trial will soon be made with the silver in a large way, and the results, whatever it may be will be candidly stated."

The results obtained with the larger melts, made at Sheffield, were published in a second article[2]. Here again, similar conclusions were reached. The forging characteristics of the alloy steels were investigated and found to be very good.

Some of the steels produced by these pioneer workers were discovered years later. Sir Robert Hadfield made a thorough investigation of all the specimens obtainable and published an article on his findings[3]. Later he wrote a book describing in more detail the work of Faraday[4]. The results of his investigation revealed that the two early investigators had made silver steel alloys with the silver content ranging from 0.14 per cent to 0.40 per cent. With the better facilities in use at the present time, fibers of silver were found in all of these specimens.

One is surprised to learn that such a small percentage of an alloying element in steel gave such remarkable success as indicated by Faraday and Stodart. Especially when later investigations revealed the presence of pure silver in the microstructure of the steel. It should be remembered that at this early date there was no testing equipment as is now available, and all results were qualitative.

No evidence can be found of any further work on silver steel alloys by these authors, or of the continuation of the production of large melts as indicated in a letter[4] to Michael Faraday from Green Picksley and Company.

In 1907, an investigation of silver-steel alloys was conducted by G. J. Petrenko. In the article covering his work[5], the author concluded that there was no solubility of the two metals below 2900 degrees F. When the molten alloys were cooled very slowly the resulting solid consisted of two layers.

In 1912 Charles F. Burgess and James Aston reported research they had conducted on silver-iron alloys[6]. They were primarily interested in the corrosion resistance of said alloys. The report indicated that the maximum solubility of silver in electrolytic iron was 0.69 per cent, although they made alloys containing as high as 10 per cent. Their conclusions were that additions of silver did not affect the corrosion resistance of iron in the atmosphere or in sulphuric acid.

Colin G. Fink and V. S. de Marchi in 1938 reported the results of an investigation to determine the solubility of silver in iron[7]. These alloys were made by compressing fine powders of the two materials at a pressure of 41 Tons per square inch and then sintering at 1750 degrees F. for four hours in a hydrogen atmosphere. Corrosion resistance and electrical resistance measurements led the authors to conclude that the solubility of silver in iron was between 0.5 per cent and 1.0 per cent. However, in their report is shown a photomicrograph of a steel containing 0.25 per cent silver in which small particles of silver are present. The results of their investigation are therefore questionable. In a discussion on this paper A. A. Dornblatt reports that the results of an investigation conducted under his direction indicate that the solubility of silver in steel is less than 0.01 per cent. His investigation shows that the silver additions decreased the porosity of steel castings. Silver was added in the following percentages: 0.025, 0.050, and 0.25. However, an analysis of the final product revealed less than 0.01 per cent in every case, indicating that the silver had probably combined with the gases in the molten metal and passes into the slag, thus leaving a more solid casting.

In a very recent article [8], the effect of additions of silver to 18 per cent Chromium, 8 per cent Nickel stainless steel is discussed. The report indicates that as little as 0.42 per cent silver reduces the salt water corrosion of this steel by more than 80 per cent and that 0.14 per cent silver, increases the heat conductivity by 26 per cent. The alloys tested were easier to machine than the regular stainless steel and took a much better polish. The cause of the great increase in salt water corrosion resistance is attributed to the formation of a protective layer of insoluble silver chloride. It is understood that further investigation is being done at the present time on these steels.

From the research work which has been performed on silver-iron alloys, it seems probable that the solubility of these two metals is very low. However, since the foregoing results are erratic, a determination was made of the solubility of silver in iron.

Theoretical Considerations

In order to determine the reasons for the apparent insolubility of silver in iron, an investigation of the theoretical aspects of alloying is necessary.

The true alloying of two or more metals occurs only when the metals in question exhibit mutual liquid solubility to a certain degree. If one metal is soluble in another in liquid state, the material resulting after the two components are mixed and molten is such that the individual elements are indistinguishable. In certain cases the alloy is produced by compressing and sintering mixtures of the powders of the metals.

In the solid state, the dissolving of one metal in another can occur in either of two ways: by forming a solid solution or an intermetallic compound. Two types of solid solutions are known to exist. These are the interstitial and the substitutional types. Interstitial solid solutions are formed when atoms of the solute metal enter in the interstities of the lattice of the solvent metal. It is apparent that this type is limited to those alloys in which the solute atoms are much smaller than the solvent atoms. Examples of this type are some of the alloys of boron and carbon with iron. The substitutional solid solutions are formed when the atoms of the solute replace the atoms of the solvent on the lattice of the latter. Most of the non-ferrous alloys and many of the ternary ferrous alloys form this type of solid solution.

Intermetallic compounds are alloys in which the metals are in such proportions as to give a simple chemical formula. Each compound in any alloy system is limited to one definite composition and has a definite melting or decomposition temperature. The crystal structures of such alloys are analagous to chemical compounds in that the position of the atoms of the components are fixed relative to one another.

It should be noted that more than one of the above types of alloys may be formed in certain alloy systems. For example, in the iron-carbon alloys, the two components form a compound, Fe_3C. At lower percentages of carbon an interstitial solid solution is formed.

In considering these three methods by which solid solubility of silver in iron may occur, the first factor to be noted is the atomic radius of each of the materials. The atomic radii are as follows:[9]

Silver	1.442 A
Alpha Iron	1.239 A
Gamma Iron	1.260 A

One would not expect silver and iron to form an interstitial solid solution. All of the radii are of the same order of magnitude. It seems highly improbable that the larger silver atoms could arrange themselves within the iron lattice.

Two factors which at present are known to affect the formation of substitutional solid solutions are the atomic size factor and the shape factor. It seems reasonable that the size of the atoms of the two metals in question should have a bearing on their mutual solubility. One would not expect a large atom to replace a small one on the lattice of the smaller, or vice versa, due to the great distortion which would necessarily occur.

From the study of numerous binary alloy systems, a flexible rule[9] has been formulated relative to the effect of the size factor. Briefly, this rule states: if conditions are to be favorable for the formation of a substitutional solid solution, then the atomic radius of both solute and solvent should not differ by more than 14 to 15 per cent.

If the size factor is favorable, substitutional solid solutions may be formed. If the atomic radii of the two metals lie outside the favorable zone, the solid solubility will be greatly restricted. In the region close to the edge of the favorable zone, the rule holds less rigidly.

Figure 1 shows the limits of the favorable range for alpha iron and gamma iron.

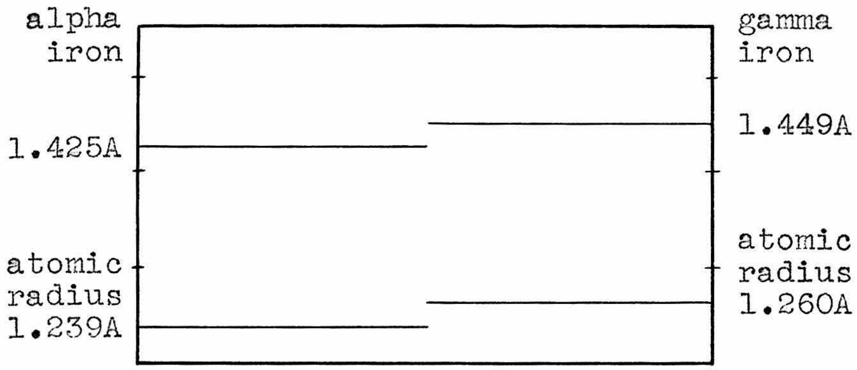

Figure 1

It is apparent that the atomic radius of silver (1.442 A) lies at the very edge of the favorable range of both alpha and gamma iron. Therefore, the formation of a substitutional solid solution would be restricted.

The second atomic property which effects the formation of a substitutional solid solution has been conveniently called the shape factor. This refers to the types of lattice of the two materials. Complete solubility of two metals in the solid state can occur only when both metals possess the same type of lattice. When the solvent and solute have different lattices, restricted miscibility occurs.

Consider now the effect of the above factor on the alloy system in question: namely, silver-iron. Silver has a face centered cubic lattice. Iron occurs in three allotropic forms. Delta iron, the high temperature form, is body centered cubic. Gamma iron, the intermediate temperature form, is face centered cubic; and alpha iron, the low temperature form, is body centered cubic. Alpha and delta iron are essentially the same, having the same type of lattice and same parameters if the values of each are extrapolated to the same temperature.

One would expect therefore, that silver would exhibit greater solubility in gamma iron than in alpha iron.

The last method to be discussed by which metals may exhibit solid solubility is by the formation of intermetallic compounds. The only theory advanced on the formation of intermetallic compounds states:[9] the more electronegative the solute element and the more electropositive the solvent, or vice versa, the greater is the tendency for the formation of stable intermetallic compounds. There seems to be slight chance, therefore, of silver and iron forming an intermetallic compound.

From a theoretical investigation it seems probable that the solid solubility of silver in iron would be extremely limited. The solubility would be greater in gamma iron than in alpha iron. If solid solutions were formed they would be of the substitutional type.

Experimental Investigation

As stated previously, the object of this portion of the investigation is to determine the solubility of silver in iron and steel.

As a preliminary step in fulfilling this objective, a Swedish iron of high purity[**] was melted in a silica crucible with an induction furnace. After the iron was molten, the required amount of silver was added and the mixture retained in the molten state for several minutes. The agitation produced in the metal by the action of the furnace was sufficient to insure thorough mixing. The alloys were cast into a cast iron mold. Table I shows the intended composition of the melts and the results obtained.

TABLE I SWEDISH IRON
50 gram melts, except as noted
*150 gram melts

Per cent Ag	Specimen No.	Remarks
0.1	1A	Silver globules on surface after casting
0.1	1A1*	" " " " " "
0.1	1A2*	" " " " " "
0.2	2A	" " " " " "
0.4	3A	" " " " " "
0.8	4A	" " " " " "
1.6	5A	" " " " " "

[**] Composition of Swedish Iron

C.	0.02-0.05 per cent	S.	0.015-0.020 percent
Mn	0.20-0.70 per cent	Si.	0.15-0.25 per cent
p	0.002-0.005 per cent		

It may be seen from this table that the amount of silver varied from 0.1 per cent to 1.6 per cent. Each of the castings showed definite evidence of silver on the surface. The amount of silver appearing on the surface of the casting increased with the silver content. In each of the above alloys it is apparent that some of the silver was never in solution with the iron. These first melts indicate that the solubility of silver in iron is less than 0.1 per cent.

Silver in the amounts shown in Table II was added to a 0.15-0.20 per cent carbon steel. The method of alloying and casting used previously was adopted for this series of melts. An examination of the table indicates that the solubility of silver in this steel and probably in iron is less than 0.02 per cent. The limits of solubility have been determined only by means of visual examination of the surface. With those alloys containing an amount of silver slightly in excess of the solubility limit, very fine globules of silver were detected after pickling in hydrochloric acid and swabbing the surface with a 10 per cent solution of ammonium persulphate. The ammonium persulphate blackened the surface of the steel, leaving any silver globules white.

Table . II Mild Steel

100 gram melts, except as noted
Cast inro cast iron mold, unless otherwise indicated

Per Cent Ag	Specimen No.	Remarks
1.0	8A2*	Silver found on surface.
1.0	8A3	" " " "
0.5	1B1	" " " "
0.5	1B2	" " " "
0.2	2B1	" " " "
0.2	2B2	" " " "
0.2	2B3	" " " "
0.2	2B4***	Slow cooled. Silver found on surface.
0.2	2B5**	Slow cooled. Silver found on surface.
0.2	2B6	Quenched from molten state, Silver found on surface.
0.13	8A1	Cooled in crucible. Cross-section examined microscopically. No silver in microstructure.
0.1	8A**	Silver found on surface.
0.1	3B1	" " " "
0.1	3B2	" " " "
0.1	3B3	" " " "
0.05	4B1	" " " "
0.05	4B2	" " " "
0.05	1J1	Sand cast. Silver found on surface.
0.05	1J2	Sand cast. Silver found on surface.
0.03	5B1	Silver found on surface.
0.03	5B2	Silver found on surface.
0.02	7B1	No silver found on surface.
0.02	7B2	Silver found on surface.
0.02	7B3	Silver found on surface.
0.02	7B4	No silver found on surface.
0.02	7B5	Silver found on surface.
0.02	9B1	Slow cooled. No silver found on surface.
0.02	9B2	Slow cooled. No silver found on surface.
0.02	9B3	Slow cooled. No silver found on surface.
0.02	9B4	Slow cooled. No silver found on surface.
0.02	2J1	Sand cast. No silver found on surface.
0.02	2J2	Sand cast. No silver found on surface.
0.015	8B1	No silver found on surface.
0.015	8B2	Silver found on surface.
0.015	8B3	No silver found on surface.
0.01	6B1	No silver found on surface.
0.01	6B2	No silver found on surface.
0.01	6B3	Silver found on surface.
0.01	6B4	No silver found on surface.
0.01	6B5	No silver found on surface.
0.01	6B6***	No silver found on surface.

* 50 gram melt
** 150 gram melt
*** 200 gram melt

A further investigation of these alloys was made by taking sections through the casting for microscopic examination. Figures 2 and 3 show microstructures of two representative specimens. The steel shown in Figure 2 contained 0.5 per cent silver. The small white globules in the structure indicate the excess silver. Such globules are found in the structure of alloys containing more than 0.02 per cent silver. The alloys containing less than 0.02 per cent silver exhibit no silver globules when examined microscopically. Figure 3 shows the structure of a typical alloy of the latter type. The gray particles, which have an appearance similar to that of a free silver, are actually inclusions and are easily distinguishable under the microscope. This result seems to give further merit to the observational method of determination of solubility of silver in iron or low carbon steel.

Results

From the results of this investigation, it may be said that the limit of solubility of silver in iron or low carbon steel is in the neighborhood of 0.02 per cent.

Further research work was considered on silver-iron alloys to determine the difference in solubility of silver in alpha and gamma iron. As indicated previously, a higher solubility might be expected in gamma

Figure 2.
Mild Steel Containing 0.5 per cent Silver
Magnification 500x
As Cast

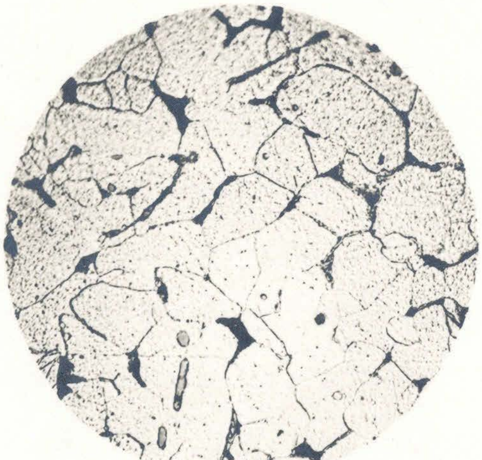

Figure 3.
Mild Steel Containing 0.015 per cent Silver
Magnification 500x
As Cast

iron. If this were true, the alloys produced would possess thermal characteristics similar to those of iron-carbon alloys, and might exhibit similar properties. However, the experimental investigation revealed that all of the silver did not combine with the iron if the silver content exceeded 0.02 per cent. Therefore any increase in solubility of silver in gamma iron above that in alpha iron would be small. Consequently it seems undesirable to investigate further the silver-iron alloys at the present time.

PART II.

SILVER-COPPER STEELS

Introduction

One of the objects of this research program was to develop an alloy which would contain an appreciable ammount of silver and possess desirable properties. The results of the previous work indicate that the solubility of silver alone in steel is low and therefore would not produce any desirable alteration in its properties. Consequently it appears that a metal must be found which would carry the silver into solution with steel. In this thesis the third metal has been designated as a carrier element.

A carrier element must form a true alloy with silver and also form an alloy with low carbon steel. The selection of a carrier requires a study of the equilibrium diagrams of both silver alloys and iron alloys. Those metals which form alloys with silver and also the iron include aluminum, antimony, arsenic, beryllium, copper, gold, manganese, platinum, silicon, tin, and zinc. It is to be expected that those metals which are completely soluble in the solid state with both iron and silver will act as the most successful carriers. None of the metals which have been listed fulfill this condition. Copper seems to be the most suitable. Furthermore, it should be recognized that at the present time copper is being used commercially as an alloying element in steel. Many beneficial properties have been derived from its use, particularly in producing a steel which is more resistant to atmospheric corrosion than plain carbon steel. In view of the present commercial importance of the copper alloys, and in view of other considerations already given, it seems most logical to select copper as the carrier-element in the attempt to produce an alloy of silver and iron. The other elements which have been listed as possible carriers are eliminated because of economic reasons, or because of their known detrimental effect on the properties of steel.

Theoretical Considerations

An investigation of the equilibrium diagram for silver-copper steels requires a study of a quaternary system. The diagram for such a system cannot be represented in any manner except by a group of ternary and binary systems. In the investigation of silver steels it was found that a small percentage carbon had little effect on the solubility. Also it has been found that additions of small percentages of carbon has little effect upon the solubility of copper in iron.[10] Therefore it appears that a study of the ternary system silver-copper-iron would give a fairly reliable picture of the alloys to be investigated.

The study of any ternary alloy system necessitates an investigation of the binary equilibrium diagrams of each pair of the metals. The three binary systems which are of interest in this work are silver-copper, copper-iron, and iron-silver. The silver-copper alloys have received much attention and the accepted diagram is shown in Figure 4.[11] It is apparent that silver and copper form solid solutions in any proportion in which they are mixed. Therefore, it would be possible to prealloy these two metals in such a manner that pure silver would not be present.

The diagram for the copper-iron system is shown in Figure 5.[10] Only the iron end of the diagram is of importance in this investigation. It is seen that approximately 8 per cent copper is soluble in gamma iron. The

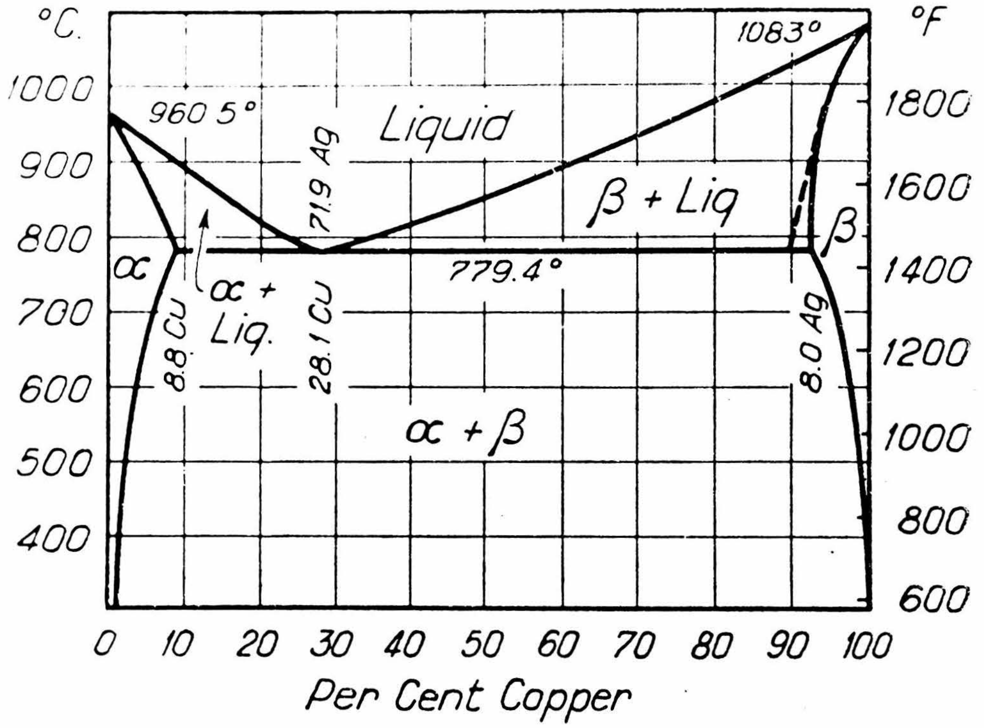

Figure 4

Equilibrium Diagram of the Silver-Copper System

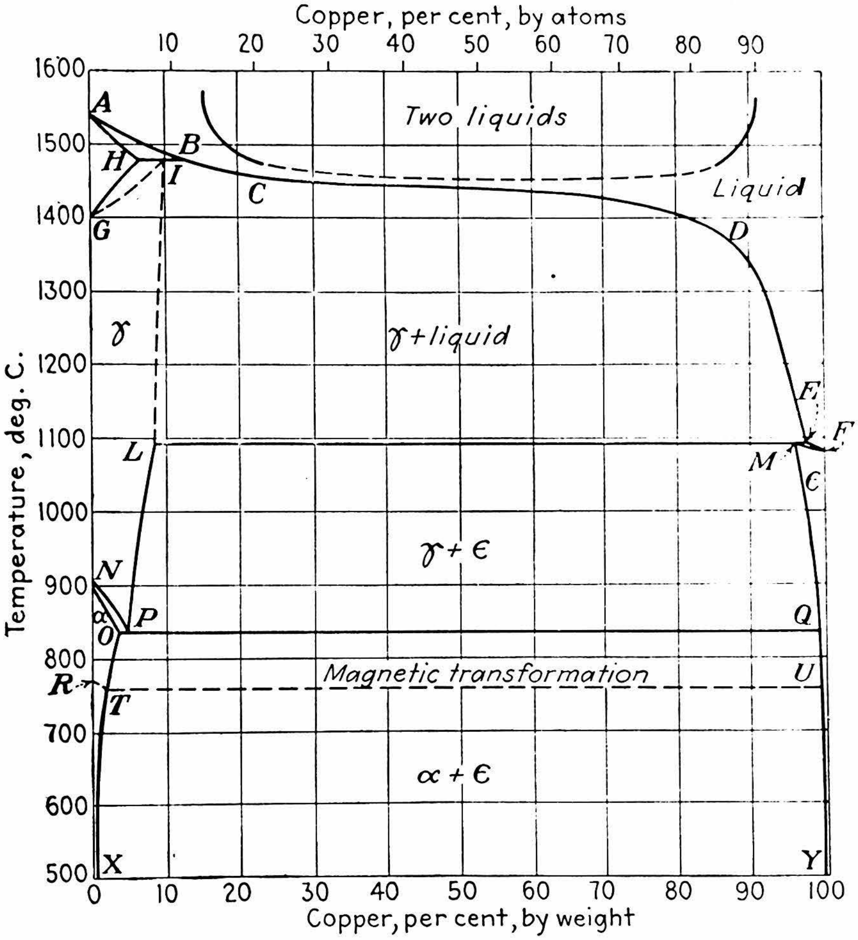

Figure 5

Equilibrium Diagram of the Copper-Iron System maximum solubility in alpha iron is 3.5 per cent. This value decreases with temperature. It is apparent that a very large addition of copper would result in the formation of an appreciable amount of a copper rich solid solution which would prove detrimental to the iron. However, the controlling factor on the amount of copper which can be added to steel is not the solubility limit; but rather the fact that this element imparts hot-shortness to steels. For this reason, the copper content does not exceed 2.5 per cent in commercial steels. If this maximum is maintained in the present investigation it is reasonable to expect the formation of no undesirable constituents.

The third binary equilibrium diagram, that of iron and silver, has never been thoroughly studied. The investigation performed by the author, and those investigations previously discussed, indicate that the diagram consists of horizontal lines at the melting points of the two components and at the transformation temperatures of iron. The solubility of silver in iron is approximately 0.02 per cent. Above this percentage relatively pure silver is present in the microstructure of the iron-silver alloys.

The ternary diagram of silver-copper-iron has only been studied by one investigator. The work, conducted by E. Luder[12], was incomplete, and offers little help in the research presented in this thesis. Luder studied only seven alloys. From the investigation, he drew a diagram of the system indicating the liquid equilibria. Figure 6 is a reproduction of his diagram. The alloys studied are indicated. In the liquid state the alloys divide themselves into a single and a double phase region. In the two phase region the molten alloy consists of an iron rich solution and a solution rich in either copper or silver; depending upon which is the higher percentage.

Alloys 1, 2, 3, 4, and 6 (indicated in Figure 6) are in the two phase liquid region. On cooling, these alloys solidified into two layers. The top layer in all cases exhibit iron crystals, along with copper particles. The silver, which by analysis was found to be present in this layer, was alloyed with the copper. The lower layer of alloy 1, showed primary silver crystals surrounded by a silver-copper eutectic. Isolated drops of iron were also found. Melts 2, 3, 4, and 6 were similar except that the excess copper solidified

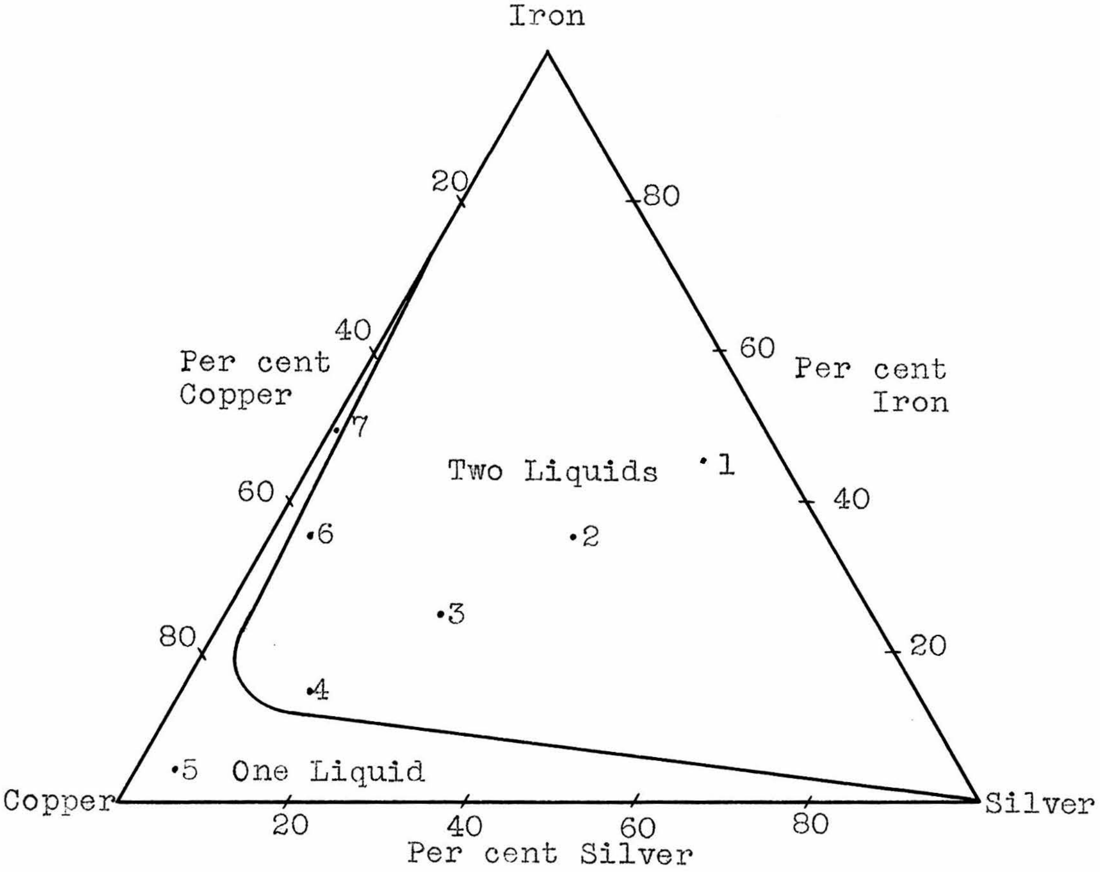

Figure 6.

Liquid Equilibria, Copper-Silver-Iron System first in the lower layer. The structure of this layer consisted of primary copper crystals and the silver copper eutectic.

The heavy line drawn from the silver corner toward the copper corner and then upwards toward the iron corner, indicates the boundary between the two phase and single phase liquid region.

Melts 5 and 7 solidified in a single layer which was rich in copper. Luder questions the correctness of his determination of alloy 7 since, he states, that a different melting technique was used. However, the diagram indicates what might be expected of the alloys of these three metals.

The study of the equilibrium diagrams of importance for this investigation has offered no indication as to the solubility of silver together with copper in steel. It is necessary, therefore, to make a determination of this solubility before any systematic research can be conducted on these alloys.

Determination of the Solubility of Silver and Copper in Steel

As mentioned previously, no complete investigation has been made of the solubility of silver together with copper in steel. Consequently, the initial work was done with these alloys in order to determine the effect of copper as a carrier element for silver in steel.

In making the alloy steels for this work it was found necessary to add the copper and silver to the steel in the form of an alloy. If copper and silver are added separately to the steel, it is found that the copper has very little effect upon the solubility of silver in steel. For this determination two methods were tried. First, the silver was added, followed by the copper. Second, the order of addition was reversed. In both cases the copper apparently had a greater affinity for the steel than the silver and immediately formed a liquid solution, leaving the silver in the unalloyed state. This exemplifies the use of a carrier.

The copper-silver alloys of desired composition were prepared by melting in a carbon crucible in an induction furnace and cast into a cast iron mold.

The alloy steels were made by melting low carbon steel in a silica crucible with the induction furnace, and adding the desired amount of the proper copper-silver alloy. To insure complete mixing of the components, all alloys were maintained in the molten condition for five minutes after the addition of the copper-silver alloys. The turbulence produced by the action of the current insured a thorough mixing. The alloys were then cast into a cast iron mold. During melting and while cooling after casting, the alloy was protected from oxidation by a borax flux.

The limit of solubility of silver in the steel was again determined by visual observation, due to its reliability in the previous tests. The results of this work are shown in Table III and Figure 7. In the figure, the percentage copper is plotted against the percentage silver for each alloy. Each point on the graph indicates two or more melts. A curve has been drawn to indicate the maximum solubility of silver with any given percentage of copper in low carbon steel. Melts which have alloy additions lying above the curve show evidence of free silver on the surface of the casting, whereas those melts which have a composition lying below the curve apparently form true alloys. It should be stated, however, that such a curve cannot be located accurately by the visual method of determining solubility limits. However, general limits of solubility can be indicated.

Table III Copper-Silver-Iron-Carbon

100 Gram Melts
Cast into Cast Iron Mold

Per Cent Cu	Per Cent Ag	Specimen No.	Remarks
1.0	1.0	2D1	Silver found on surface.
1.0	1.0	2D2	" " " "
2.0	1.0	2D3	" " " "
2.0	1.0	2D4	" " " "
3.0	1.0	2D5	" " " "
3.0	1.0	2D6	" " " "
1.0	2.0	3D1	" " " "
1.0	2.0	3D2	" " " "
2.0	2.0	3D3	" " " "
2.0	2.0	3D4	" " " "
3.0	2.0	3D5	" " " "
3.0	2.0	3D6	" " " "
0.5	0.5	4D1	" " " "
0.5	0.5	4D2	" " " "
0.6	0.4	4D3	" " " "
0.6	0.4	4D4	" " " "
0.75	0.25	4D5	" " " "
0.75	0.25	4D6	" " " "
0.375	0.125	5D1	" " " "
0.375	0.125	5D2	" " " "
0.375	0.125	5D3	" " " "
0.375	0.125	5D4	" " " "
0.3	0.1	6D1	" " " "
0.3	0.1	6D2	" " " "
0.3	0.1	6D4	" " " "
0.15	0.05	7D1	" " " "
0.15	0.05	7D2	" " " "
0.4	0.1	1E1	No silver found on surface.
0.4	0.1	1E2	Silver found on surface.
0.5	0.1	1E3	No silver found on surface.
0.5	0.1	1E4	No silver found on surface.
0.8	0.2	2E1	Silver found on surface.
0.8	0.2	2E2	Silver found on surface.
1.0	0.2	2E3	Silver found on surface.
1.0	0.2	2E4	Slow cooled. Silver found on surface.
1.0	0.2	2E5	Silver found on surface.
1.2	0.2	2E6	No silver found on surface.
1.2	0.2	2E7	No silver found on surface.
2.1	0.3	3E1	Silver found on surface.
2.1	0.3	3E2	Silver found on surface.

Table III(continued). Copper-Silver-Iron-Carbon

100 Gram Melts

Cast into Cast Iron Mold

Per Cent Cu	Per Cent Ag	Specimen No.	Remarks
2.4	0.3	3E3	Silver found on surface.
2.4	0.3	3E4	No silver found on surface.
2.4	0.3	3E5	No silver found on surface.
4.0	0.4	4E1	Silver found on surface.
4.0	0.4	4E2	Silver found on surface.
4.0	0.4	4E9	Silver found on surface.
4.0	0.367	6E5	Silver found on surface.
4.0	0.367	6E6	Silver found on surface.
4.0	0.32	8E5	No silver found on surface.
4.0	0.32	8E6	No silver found on surface.
5.0	0.5	5E1	Silver found on surface.
5.0	0.5	5E2	Silver found on surface.
5.0	0.458	5E5	No silver found on surface.
5.0	0.458	5E6	No silver found on surface.
5.0	0.458	8E7	Silver found on surface.
5.0	0.458	8E8	Silver found on surface.
5.0	0.4	4E5	No silver found on surface.
5.0	0.4	4E6	No silver found on surface.
5.0	0.4	8E4	No silver found on surface.
5.0	0.35	3E7	No silver found on surface.
5.0	0.35	3E8	No silver found on surface.
5.5	0.44	4E7	Silver found on surface.
5.5	0.44	4E8	Silver found on surface.
5.5	0.44	8E3	No silver found on surface.
5.5	0.385	4E3	No silver found on surface.
5.5	0.385	4E4	No silver found on surface.
6.0	0.55	6E1	Silver found on surface.
6.0	0.55	6E2	Silver found on surface.
6.0	0.48	9E4	No silver found on surface.
6.0	0.48	9E5	No silver found on surface.
6.5	0.596	6E3	No silver found on surface.
6.5	0.596	6E4	No silver found on surface.
7.0	0.8	8E1	Silver found on surface.
7.0	0.8	8E2	Silver found on surface.
7.0	0.7	7E1	Silver found on surface.
7.0	0.7	7E2	No silver found on surface.
7.0	0.7	7E3	No silver found on surface.
7.0	0.5	5E3	No silver found on surface.
7.0	0.5	5E4	No silver found on surface.
8.0	1.0	9E1	Silver found on surface.
8.0	0.914	9E2	Silver found on surface.
8.0	0.914	9E3	Silver found on surface.

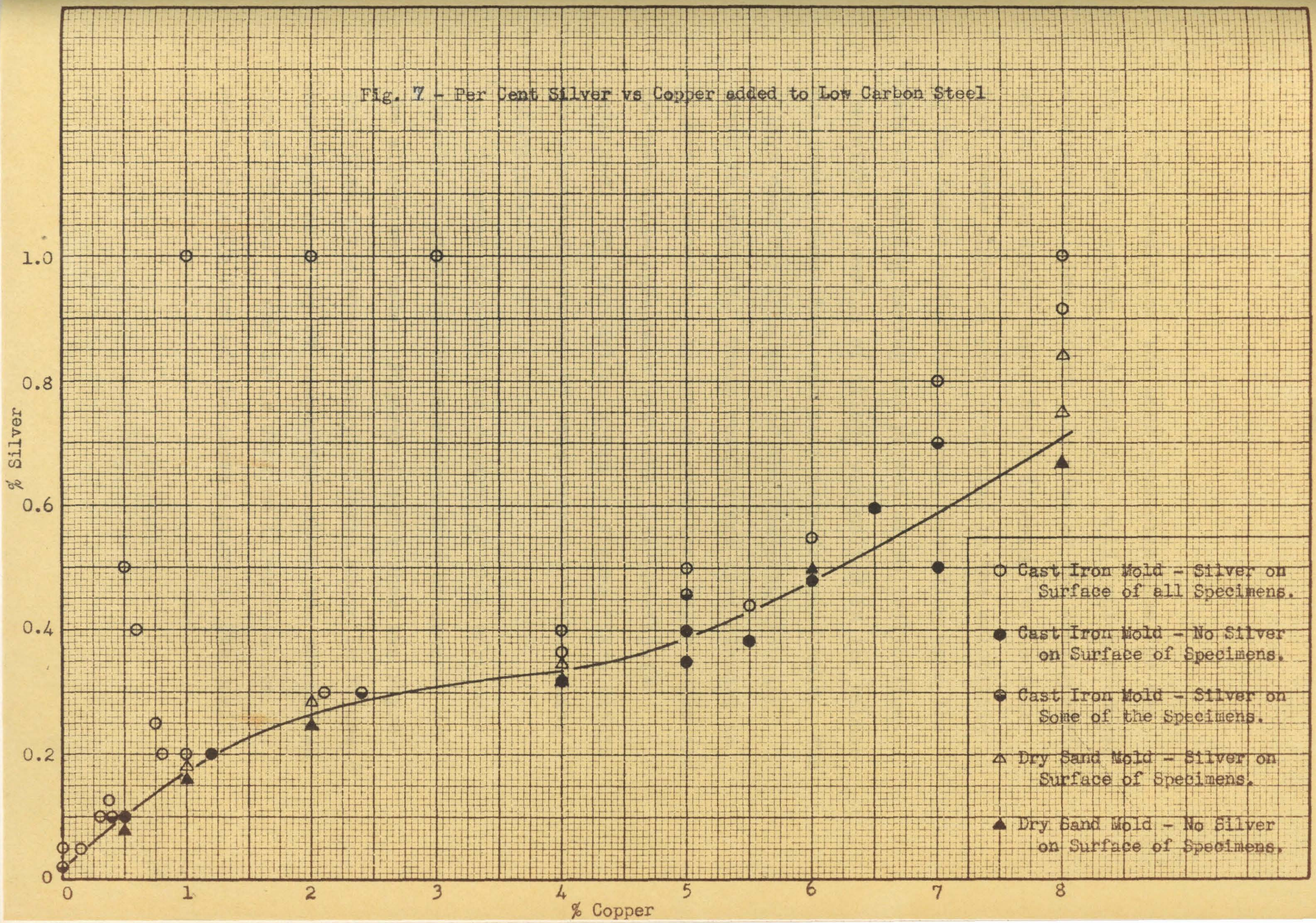

Fig. 7 - Per Cent Silver vs Copper added to Low Carbon Steel

The results of the work conducted thus far are based upon casting in a cast iron mold, which produces a severe chilling effect. In view of the configuration of the iron copper equilibrium diagram, it was felt that there might be some variation in the solubility of the copper and silver in iron, depending upon the rate of cooling during the period of solidification. Therefore, a series of alloys was melted in the manner previously described, and cast into dry-sand mold. The alloys used for this part of the investigation are given in Table IV. These results are also plotted in Figure 7 as noted. It can be seen that the results are in very close agreement with the data previously obtained. The variations shown in Figure 7 are within the limits of accuracy of this method of determining solubility.

In order to check the results of this work more closely, a study of the microstructure of several of the alloys was made. Figures 8 and 9 show two representative structures. The structures shown in Figure 8 represent an alloy of composition above the determined curve (Figure 7) and it is used to illustrate the characteristic form of the excess silver. The small

Table IV Copper-Silver-Iron-Carbon

100 Gram Melts

Cast in Dry Sand

Per Cent Cu	Per Cent Ag	Specimen No.	Remarks
0.5	0.1	1H1	Silver found on surface.
0.5	0.1	1H2	Silver found on surface.
0.5	0.08	1H3	No silver found on surface.
0.5	0.08	1H4	No silver found on surface.
1.0	0.182	2H1	Silver found on surface.
1.0	0.182	2H2	Silver found on surface.
1.0	0.16	2H3	No silver found on surface.
1.0	0.16	2H4	No silver found on surface.
2.0	0.286	3H1	Silver found on surface.
2.0	0.286	3H2	Silver found on surface.
2.0	0.25	3H3	No silver found on surface.
2.0	0.25	3H4	No silver found on surface.
4.0	0.35	4H1	Silver found on surface.
4.0	0.35	4H2	Silver found on surface.
4.0	0.32	4H3	No silver found on surface.
4.0	0.32	4H4	No silver found on surface.
6.0	0.5	5H1	No silver found on surface.
6.0	0.5	5H2	No silver found on surface.
8.0	0.842	6H1	Silver found on surface.
8.0	0.842	6H2	Silver found on surface.
8.0	0.75	6H3	Silver found on surface.
8.0	0.75	6H4	Silver found on surface.
8.0	0.667	6H5	No silver found on surface.
8.0	0.667	6H6	No silver found on surface.

Figure 8.
Silver-Copper Steel
Magnification 500x
As Cast

Figure 9.
Silver-Copper Steel
Magnification 500x
As Cast

light globules are silver. Figure 9 is typical of those alloys of compositions below the curve (Figure 7). No silver could be found in the structure of any of the alloys in this region. The results obtained from the microstructure check those obtained from visual inspection.

The work conducted thus far has been concerned primarily in the determination of a method of alloying silver with steel. By using copper as a carrier element it was found that a small amount, 0.7 per cent, of silver could be alloyed with steel. To many, the permissable amount seems rather small, but it should be remembered that in several cases such a small amount of alloying element has added beneficial effects to steels and other metals. Another factor to be considered is the economics of the addition of such a metal as silver to steel. Under present market conditions, the addition of 1 per cent silver would approximately double the cost of the steel. Therefore, in order for silver to be used as an alloy it must be kept to low percentages unless the properties are vastly improved.

In the determination of the solubility, Figure 7, alloys were made containing up to 8 per cent copper.

However, it is known that if the copper content exceeds 2.5 per cent the steel is hot short. This was found to be true with the alloys containing silver with the copper. The steels selected for this investigation were consequently limited to a maximum copper content of 2 per cent and a silver content of approximately 0.25 per cent.

The steels which were used in making these alloys were SAE 1020 and SAE 1040 steels. These were selected because they include the range in carbon content which is most widely used for structural purposes and machine parts.

Preparation of Silver-Copper Steels for Study of Properties

It was shown in the previous investigation that if any silver were to be retained in steel it was necessary to add the silver and copper as an alloy. The copper-silver alloys were melted in the induction furnace, using a graphite crucible, and cast into a cast iron mold 1½ inch by 1½ inch by 8 inches. Each melt weighed approximately 4 pounds. Table V shows the intended composition of these alloys.

TABLE V

Alloy No.	% Copper	% Silver
1	94.3	5.7
2	92.6	7.4
3	89.3	10.7
4	86.2	13.8

Approximately 1100 pounds of each steel were obtained from Bergstrom Steel Company of Los Angeles in 4 inch round bars. The heat numbers and analyses of the steels used in this investigation are as follows:

	S.A.E. 1020 Heat #128391	S.A.E. 1040 Heat #123385
Carbon	0.18 per cent	0.38 per cent
Manganese	0.71 per cent	0.88 per cent
Phosphorus	0.017 per cent	0.020 per cent
Sulphur	0.030 per cent	0.026 per cent

The billets were sawed into pieces weighing approximately 25 pounds. The actual weight of each piece of steel and the weights of the alloys used are given in Tables VI and VII .

A piece of steel was melted in a magnesia crucible in the induction furnace and a small amount of flux containing 60 parts lime, 40 parts fire clay, and 10 parts fluorspar was placed on top of the steel. As soon as the entire mass was molten, the required alloy was added.

Table VI S.A.E. 1020 Steel

Sample No.*	Wt. of Steel lbs.	Ag-Cu Alloy Comp. Cu,%	Ag,%	Wt.,lbs.	Nominal Analysis of Steel % Cu	% Ag	Weight of Aluminum Added, lbs.	Casting Temp., °F.
20C	25.25	0	0	0	0	0	0.011	2693
20F	25.26	0	0	0	0	0	0.011	
21C	25.48	100	0	0.1280	0.5	0	0.010	2870
21F	25.48	100	0	0.1280	0.5	0	0.009	2840
22C	25.21	92.6	7.4	0.1369	0.5	0.04	0.009	2840
22F	25.16	92.6	7.4	0.1366	0.5	0.04	0.009	2778
23C	25.91	86.2	13.8	0.1512	0.5	0.08	0.009	2797
23F	25.83	86.2	13.8	0.1507	0.5	0.08	0.009	2834
24C	25.86	100	0	0.2612	1.0	0	0.009	2810
24F	25.22	100	0	0.2548	1.0	0	0.009	2882
25C	25.29	92.6	7.4	0.2761	1.0	0.08	0.009	2797
25F	25.33	92.6	7.4	0.2764	1.0	0.08	0.009	2822
26C	25.41	86.2	13.8	0.2983	1.0	0.16	0.009	2778
26F	25.43	86.2	13.8	0.2985	1.0	0.16	0.009	2713
27C	25.12	100	0	0.5121	2.0	0	0.009	2771
27F	25.14	100	0	0.5130	2.0	0	0.009	2834
28C	25.37	94.3	5.7	0.5496	2.0	0.12	0.009	2784
28F	25.35	94.3	5.7	0.5492	2.0	0.12	0.009	2784
29C	25.29	89.3	10.7	0.5805	2.0	0.24	0.009	2771
29F	25.33	89.3	10.7	0.5794	2.0	0.24	0.009	2745

* C = Sample for investigation of properties of cast steel alloy
F = Sample for investigation of properties of forged steel alloy

Table VII S.A.E. 1040 Steel

Sample	Wt.of	Ag-Cu	Alloy		Nominal Analysis		Weight of	
	Steel	Comp.			of Steel		Aluminum	Casting
No.*	lbs.	Cu,%	Ag,%	Wt.,lbs.	% Cu	% Ag	Added,lbs.	Temp.,°F.
30C	25.23	0	0	0	0	0	0.009	2784
30F	25.42	0	0	0	0	0	0.009	2758
31C	25.52	100	0	0.1282	0.5	0	0.009	2810
31F	25.53	100	0	0.1283	0.5	0	0.009	2784
32C	25.51	92.6	7.4	0.1385	0.5	0.04	0.009	2797
32F	25.50	92.6	7.4	0.1384	0.5	0.04	0.009	2771
33C	25.46	86.2	13.8	0.1485	0.5	0.08	0.009	2784
33F	25.46	86.2	13.8	0.1485	0.5	0.08	0.009	2771
34C	25.27	100	0	0.2553	1.0	0	0.009	2765
34F	25.27	100	0	0.2553	1.0	0	0.009	2797
35C	25.30	92.6	7.4	0.2762	1.0	0.08	0.009	2784
35F	25.29	92.6	7.4	0.2761	1.0	0.08	0.009	2771
36C	25.36	86.2	13.8	0.2976	1.0	0.16	0.009	2745
36F	25.37	86.2	13.8	0.2978	1.0	0.16	0.009	2758
37C	25.56	100	0	0.5216	2.0	0	0.009	2784
37F	25.19	100	0	0.5141	2.0	0	0.009	2797
38C	25.31	94.3	5.7	0.5485	2.0	0.12	0.009	2719
38F	25.34	94.3	5.7	0.5492	2.0	0.12	0.009	2784
39C	25.41	89.3	10.7	0.5825	2.0	0.24	0.009	2739
39F	25.47	89.3	10.7	0.5838	2.0	0.24	0.009	2758

* C = Sample for investigation of properties of cast steel alloy

F = Sample for investigation of properties of forged steel alloy

The turbulence produced in the metal by the furnace action mixed the alloy thoroughly. The alloy was cast when the temperature of the molten metal was approximately 2800 degrees F. as determined with an optical pyrometer. While the metal was being cast into the mold, small pieces of aluminum were added in the amounts indicated in Tables VI and VII. The purpose of this element was to deoxidize the melt.

As soon as one alloy was cast another piece of steel (preheated to about 1500 degrees F.) was placed in the furnace, melted, and alloyed in the manner just described. The steel was preheated in a salt bath at 1750 degrees F. and momentarily quenched in water to remove the salt from the surface of the bar.

The molds were made of core sand and baked. Two shapes of molds were used. One, Figure 10a, was for the purpose of making the casting for studying the properties of the forged alloys. The other mold, Figure 10b, was used to make the casting for the investigation of the cast properties of the alloys. Large risers were provided for each casting to eliminate porosity and shrinkage.

After the castings had cooled in the sand, the risers

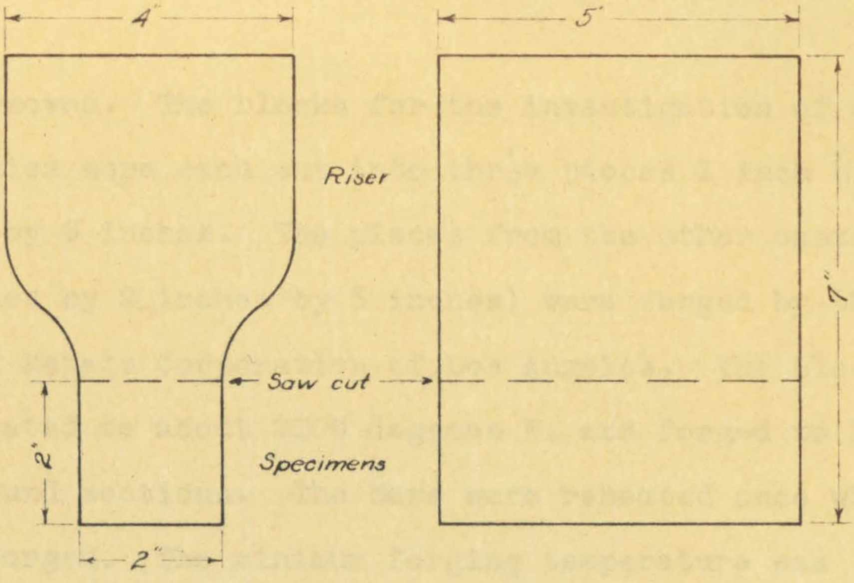

Figure 10a-Casting For Forged Samples

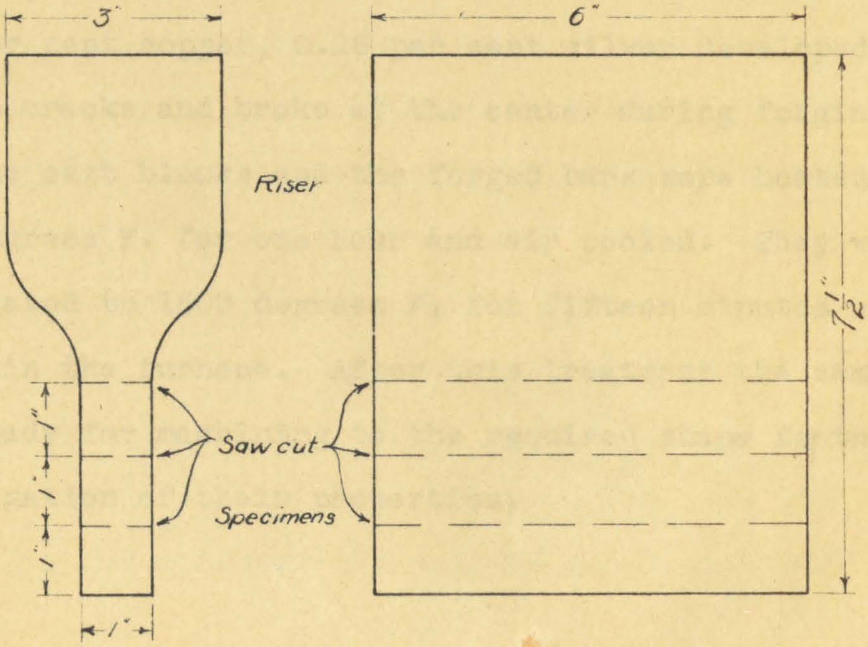

Figure 10b-Casting For Cast Samples

were removed. The blocks for the investigation of cast properties were each cut into three pieces 1 inch by 1 inch by 6 inches. The pieces from the other castings (2 inches by 2 inches by 5 inches) were forged by the General Metals Corporation of Los Angeles. The blocks were heated to about 2000 degrees F. and forged to 1 inch round sections. The bars were reheated once while being forged. The minimum forging temperature was approximately 1400 degrees F.

The only alloy steels which were difficult to forge were those which contained 2 per cent copper with or without silver. These alloys were slightly hot short and some were severely cracked. Alloy No. 29, containing 2.33 per cent copper, 0.26 per cent silver developed serious cracks and broke at the center during forging.

The cast blocks and the forged bars were heated to 1700 degrees F. for one hour and air cooled. They were then heated to 1500 degrees F. for fifteen minutes and cooled in the furnace. After this treatment the samples were ready for machining to the required shape for the investigation of their properties.

Chemical Analysis of Prepared Steels

In making the silver-copper steels, the amount of the alloying elements added to each steel was accurately weighed. However, it was expected that due to oxidation the composition of the alloy steels would be slightly different from the intended composition. Therefore it was necessary to have an accurate analysis of the alloyed steels.

Investigation indicated that the quantitative chemical analysis of small amounts of silver in steel is relatively inaccurate. Spectrochemical analysis, on the other hand, is a very accurate method of determining low percentages of any element in an alloy, and is particularly accurate for determining low percentages of silver and copper. Hence, the determination of the percentages of silver, copper, silicon, manganese, and aluminum in the steels was made with a spectrograph.

A spectrograph of the grating type, an alternating current rectifier arc stand, a projector comparator, and a densitometer manufactured by the Applied Research Laboratories in Los Angeles were used for this work. The analysis for carbon was made by the combustion method.

The samples for the spectrochemical analysis and the carbon determination were obtained by taking drillings from the center of each of the forged and the cast bars.

The analyses for the steels are given in Tables VIII and IX.

Table VIII Analysis of Forged Steels

Sample	% Cu	% Ag	% C	% Al	% Si	% Mn
20F	0.05	0.004	0.17	0.04	0.20	0.54
21F	0.54	0.004	0.16	0.02	0.10	0.53
22F	0.56	0.047	0.155	0.03	0.13	0.54
23F	0.85	0.097	0.16	0.05	0.13	0.54
24F	1.08	0.004	0.16	0.02	0.11	0.54
25F	1.29	0.103	0.165	0.03	0.13	0.53
26F	1.17	0.223	0.165	0.04	0.12	0.48
27F	2.26	0.004	0.155	0.02	0.16	0.46
28F	2.33	0.162	0.15	0.05	0.14	0.46
29F	2.33	0.267	0.17	0.04	0.11	0.45

Sample	% Cu	% Ag	% C	% Al	% Si	% Mn
30F	0.06	0.005	0.35	0.04	0.19	0.68
31F	0.82	0.005	0.345	0.04	0.12	0.67
32F	0.69	0.047	0.35	0.04	0.17	0.74
33F	0.65	0.087	0.35	0.04	0.18	0.74
34F	1.19	0.000	0.35	0.05	0.19	0.76
35F	1.26	0.067	0.355	0.04	0.15	0.75
36F	1.24	0.190	0.345	0.04	0.15	0.71
37F	2.26	0.000	0.33	0.03	0.16	0.72
38F	2.46	0.150	0.32	0.04	0.17	0.62
39F	2.11	0.265	0.325	0.04	0.13	0.59

Table IX Analysis of Cast Steels*

Sample	% Cu	% Ag	% C	% Al	% Si	% Mn
20C	0	0	0.145	0.13	0.15	0.45
21C	0.35	0	0.15	0.06	0.20	0.45
22C	0.33	0.048	0.155	0.06	0.21	0.61
23C	0.35	0.068	0.15	0.04	0.21	0.59
24C	1.00	0	0.15	0.06	0.21	0.55
25C	0.68	0.095	0.14	0.04	0.20	0.56
26C	0.98	0.165	0.15	0.05	0.17	0.49
27C	1.68	0	0.14	0.03	0.15	0.40
28C	1.88	0.118	0.14	0.04	0.14	0.49
29C	1.65	0.223	0.14	0.06	0.20	0.47

Sample	% Cu	% Ag	% C	% Al	% Si	% Mn
30C	0.025	0	0.345	0.07	0.23	0.75
31C	0.42	0	0.34	0.07	0.25	0.75
32C	0.30	0	0.35	0.07	0.18	0.75
33C	0.93	0.008	0.325	0.05	0.17	0.67
34C	0.23	0.032	0.35	0.04	0.15	0.78
35C	0.98	0.035	0.36	0.06	0.15	0.76
36C	0.66	0.123	0.35	0.06	0.26	0.73
37C	2.05	0.022	0.36	0.08	0.26	0.78
38C	2.06	0.038	0.33	0.08	0.16	0.74
39C	3.05	0.150	0.34	0.06	0.15	0.79

*These analyses differ considerably from the nominal analyses due to segregation. Investigation has shown that copper and silver segregate severely in casting.

PART III.

THE EFFECT OF ADDITIONS OF SILVER AND COPPER ON THE THERMAL CRITICAL TEMPERATURES OF STEEL

Introduction

The test for the determination of the thermal critical points of the steels is very important. Many of the alloying elements in steel owe their success to the changing of these temperatures. By lowering, they allow lower heat treating temperatures. Some metals lower the transformation points to such a low value that the austenite is stable at room temperatures. Others cause the transformation to be so sluggish that control of properties is very easy. Still others shift the eutectoid composition to lower values of carbon and thus give higher hardness and strength for lower carbon content.

In short, it can be said that the transformation of alpha iron to gamma iron and vice-versa is the chief factor in giving steel its wide adaptability. Therefore it would seem necessary that the determination of the temperatures at which this transformation occurs is very necessary for a complete understanding of the steels under study.

It will be noted, from the alloys made for this investigation that some steels were made which contained no silver whatsoever. These steels were to be used as a standard on which to base the effect of the silver. It is known that the addition of copper[10] lowers the critical points of the steels a slight amount. This fact can be used as a check on the apparatus.

In this investigation the A_1 and A_3 critical points were determined on heating and cooling for the forged alloys already described. Most data on critical points have been obtained in the past by either thermal of dilatometric analysis. In this investigation both methods were used simultaneously for the purpose of obtaining as complete data as possible.

Apparatus

The equipment for an investigation of this character must fulfil the following specifications:

1. A furnace capable of maintaining a uniform temperature throughout the length of the specimen.
2. An instrument to control and record the rate of heating and cooling of the furnace.

3. A device to indicate the dilation of a steel specimen as it is heated and cooled through the critical range.
4. A device to indicate the difference between the temperature of the steel specimen and a neutral body.
5. An instrument to record simultaneously dilation, temperature difference, and specimen temperature.

Consultation with the representatives of instrument manufacturers indicated that suitable equipment with the above specifications was not obtainable commercially. This situation led to the design and construction of the apparatus shown in Figure 11 and described below.

The furnace (A in Figure 11, and shown in detail in Figures 12, 13, and 14) was purchased from Rockwell Instrument Company. It consists of a split shell A, with a refractory lining B, and a resistance heating element C. A copper sheath D was placed in the heating space to insure temperature uniformity over the length of the specimen. A hole E is provided in the bottom of the furnace to accomodate a quartz tube F which supports the specimen G and neutral body H. A quartz rod J resting on top of the specimen passes through the hole K in the top of the furnace to the dilation-indication device.

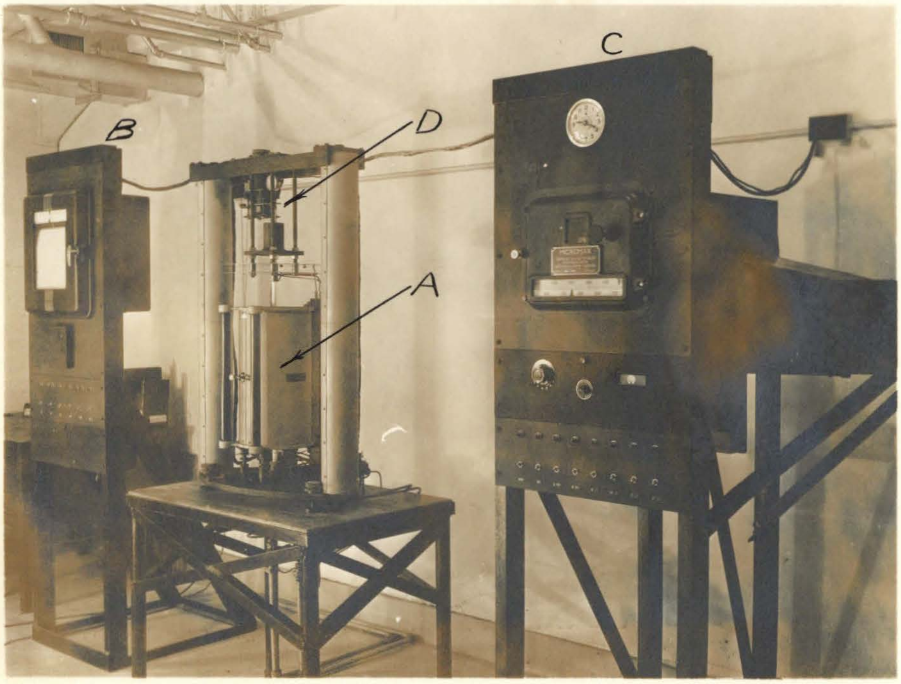

Figure 11.

General View of Equipment

Figure 12.

Furnace

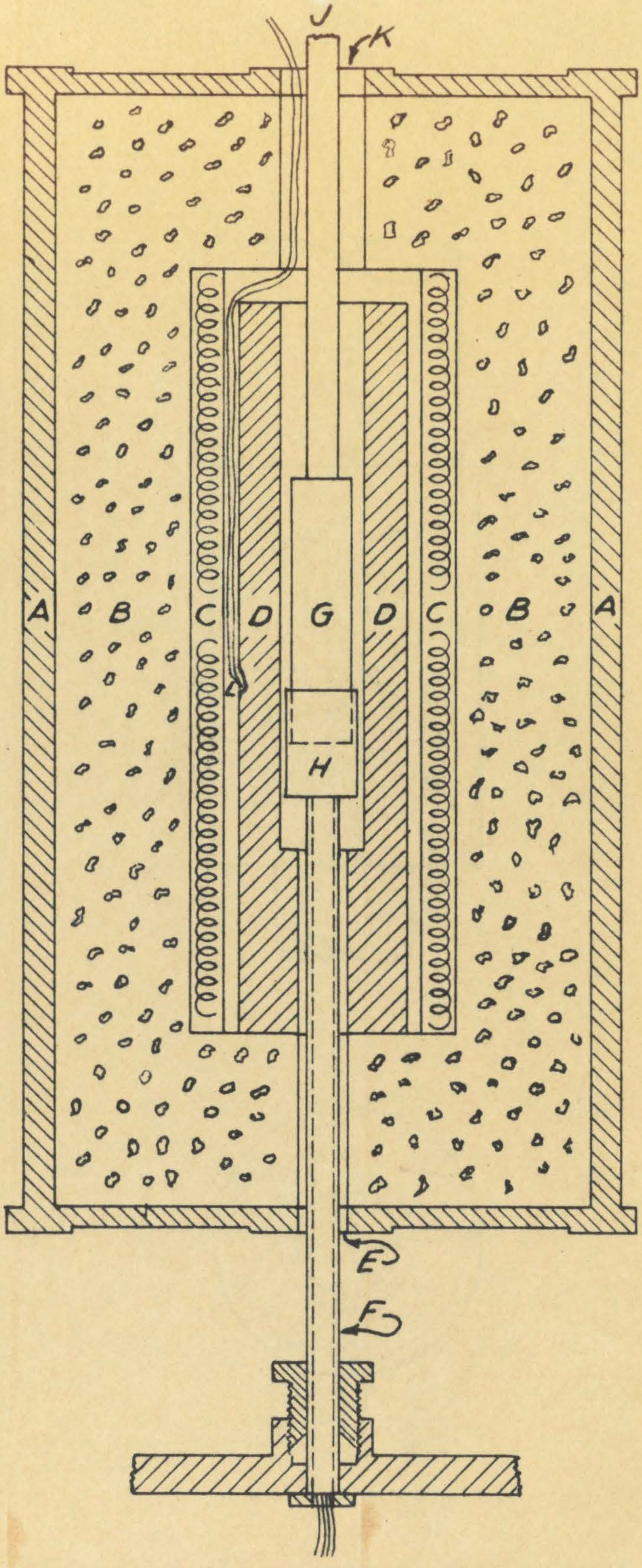

Figure13—Furnace Section

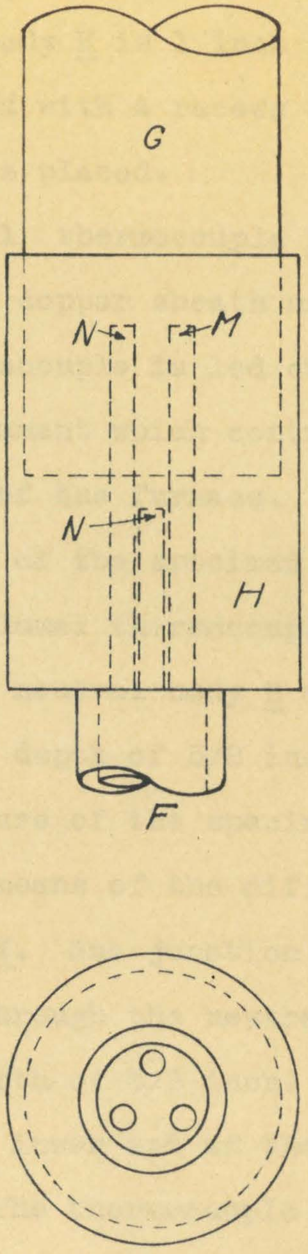

Figure 14—Thermocouple Arrangement

The specimen *G* is 7/8 inch in diameter and 4 inches long. The neutral body *H* is 1 inch in diameter, 1½ inches long, and is provided with a recess 3/4 inch deep in which the specimen is placed.

A chromel-alumel thermocouple *L* is fastened to the outer surface of the copper sheath next to the furnace winding. This thermocouple is led out the top of the furnace to the instrument which controls the rate of heating and cooling of the furnace.

The temperature of the specimen *G* is obtained by means of a chromel-alumel thermocouple *M* (Figure 14) inserted through the neutral body *H* and into the bottom of the specimen to a depth of 5/8 inch. The difference between the temperature of the specimen and the neutral body is obtained by means of the differential chromel-alumel thermocouple *N*. One junction of this thermocouple is inserted through the neutral body and into the specimen to a depth of 5/8 inch. The other junction is inserted into the lower end of the neutral body to a depth of 5/8 inch. The thermocouple wires lead from the neutral body down through the quartz tube and to the recording instrument.

The rate of heating and cooling of the furnace is controlled by a Leeds and Northrup Micromax Recording Program Controller No. 40851-S, shown at *B* in Figure 11. This instrument may be set to heat or cool the furnace at any rate between 0 and 550 degrees F. per hour. The instrument is provided with a reversing circuit to change the furnace control from the heating cycle to the cooling cycle at any predetermined temperature. This circuit is actuated by the specimen temperature indicator shown at *C* in Figure 11.

The device to indicate the dilation or change in length of the specimen, as it is heated and cooled, is shown at *D* in Figure 11 and in detail in Figure 15. The quartz rod, *J* in Figure 13, resting on the specimen extends through the furnace to the armature, *A* of Figure 15, of an induction bridge. The change in length of the specimen is transmitted by the quartz rod to the armature which is pivoted at *B*. The movement of the armature changes the induction in the two arms of the bridge circuit shown in Figure 16, thus causing a current to flow through the galvanometers, which register a deflection. The galvanometer deflection is related

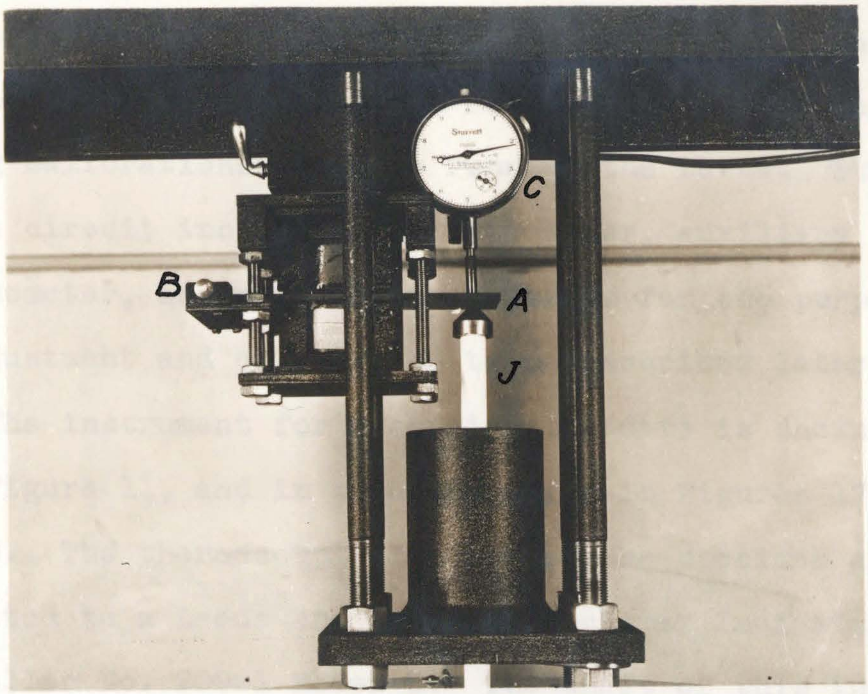

Figure 15.
Induction Bridge

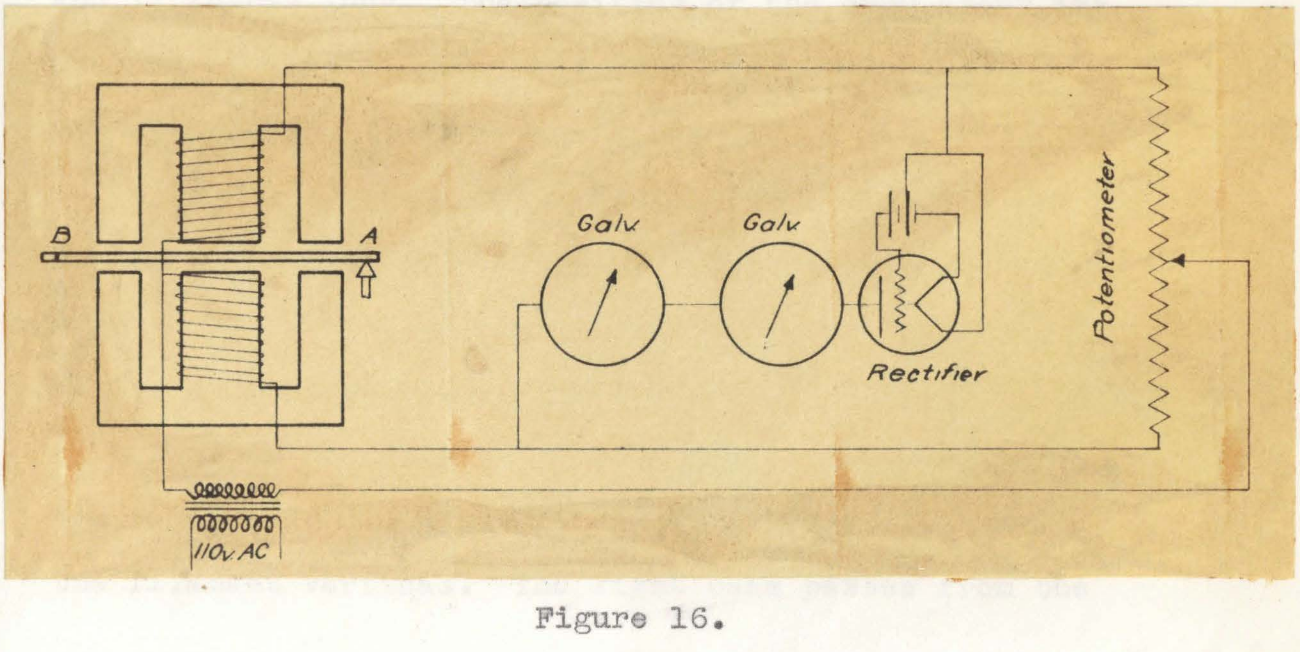

Figure 16.

Induction Bridge Circuit

to the change in length of the specimen as shown in Figure 21. A dial gage, C in Figure 15, is used for making calibrations prior to running the tests. The bridge circuit includes a potentiometer, auxiliary galvanometer, and variable transformer for the purpose of adjustment and calibration to be described later.

The instrument for recording the date is shown at C in Figure 11, and in greater detail in Figures 17 and 18. The thermocouple leads from the specimen are connected to a Leeds and Northrup Micromax Indicating Controller No. 20901 Model C. The shaft of this instrument extends through the back of the case and is connected to a drum A in Figure 18, 12 inches in diameter and 12 inches long. The position of the drum about its axis of rotation is controlled by the temperature of the specimen.

The wires from the differential thermocouple are connected to a Leeds and Northrup No. 24286 Galvanometer, B in Figure 18. A similar galvanometer C is connected to the induction bridge circuit.

A 6-volt single-filament lamp obtained from the Wm. H. Miller Company of Pasadena is mounted at D with the filament vertical. The light beam passes from the

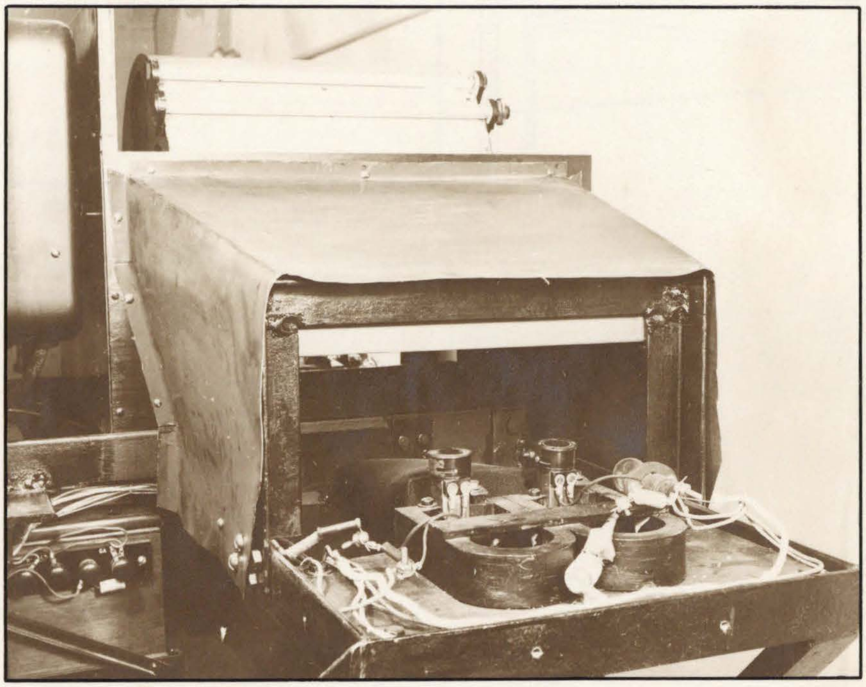

Figure 17.

Recording Apparatus

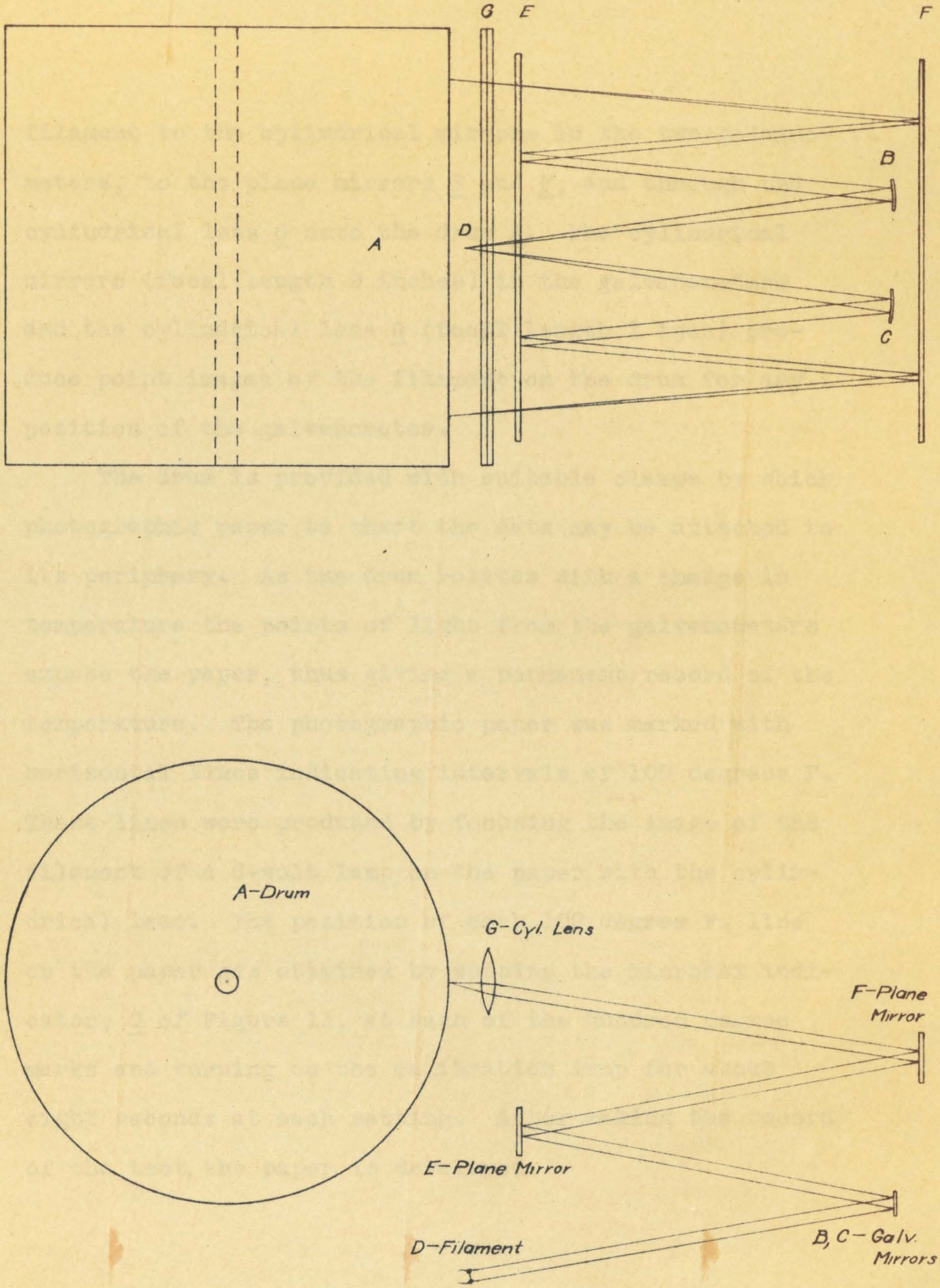

Figure 18 — Optical Recording System

filament to the cylindrical mirrors in the two galvanometers, to the plane mirrors E and F, and through the cylindrical lens G onto the drum A. The cylindrical mirrors (focal length 9 inches) in the galvanometers and the cylindrical lens G (focal length 1 inch) produce point images of the filament on the drum for any position of the galvanometer.

The drum is provided with suitable clamps by which photographic paper to chart the data may be attached to its periphery. As the drum rotates with a change in temperature the points of light from the galvanometers expose the paper, thus giving a permanent record of the temperature. The photographic paper was marked with horizontal lines indicating intervals of 100 degrees F. These lines were produced by focusing the image of the filament of a 6-volt lamp on the paper with the cylindrical lens. The position of each 100 degree F. line on the paper was obtained by setting the Micromax indicator, C of Figure 11, at each of the hundred degree marks and turning on the calibration lamp for about eight seconds at each setting. After making the record of the test, the paper is developed.

Determination of Temperature Uniformity Throughout the Specimen

In an investigation of this character it is imperative that with heating and cooling the temperature of the specimen be uniform throughout its length. A determination of this uniformity was made by inserting thermocouples in a mild steel specimen, which was then placed in the furnace and subjected to the same heating and cooling cycle used for the determination of critical points. The temperature at several points along the surface and on the axis of the specimen is plotted in Figure 19 for the indicated mean temperatures on heating. Figure 20 shows similar curves on cooling. The results of this determination indicate that the copper sheath maintains a uniform temperature along the length of the specimen within 3 degrees F.

Induction Bridge Calibration

In order to calibrate the induction bridge it is necessary to determine the relation between the displacement of the armature of the induction bridge and the deflection of the light beam of the galvanometer on the drum of the recorder for different distances between the field coils and for different field voltages.

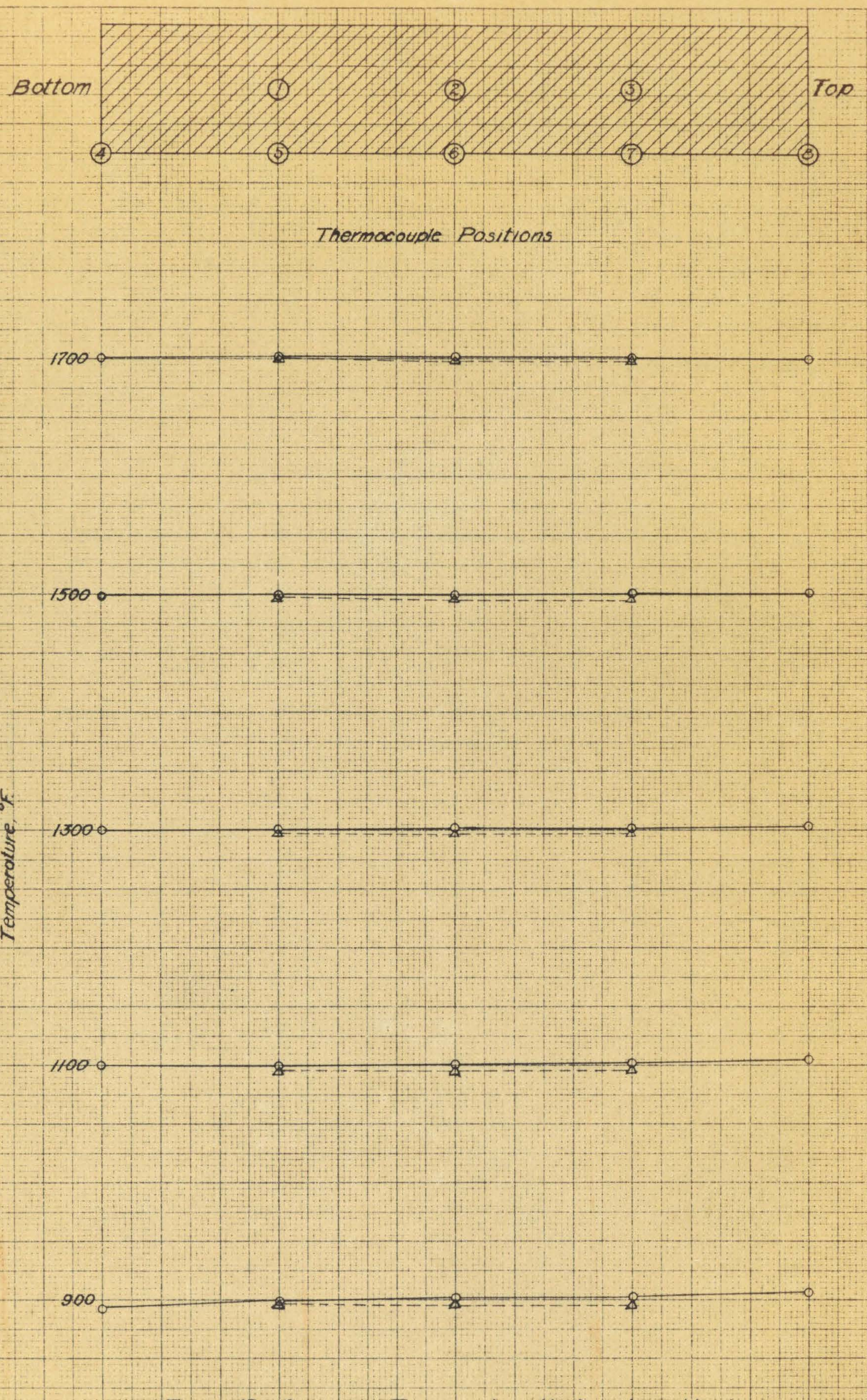

Figure 19 — Specimen Temperature Uniformity on Heating

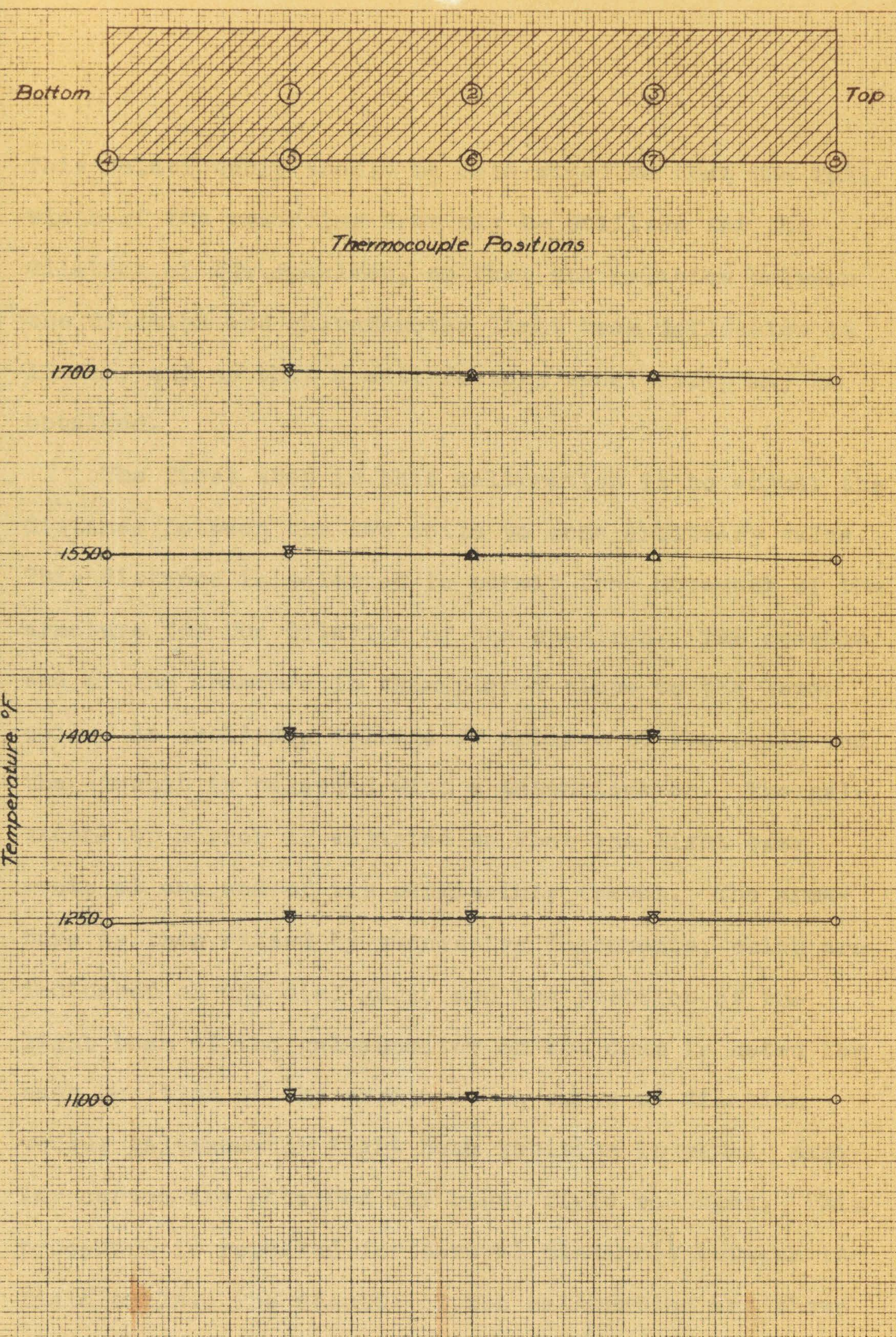

Figure 20 – Specimen Temperature Uniformity on Cooling

This relationship should be determined so that the full width of the recording drum may be utilized for the dilation of the specimen, so that the relation between the dilation and galvanometer light beam deflection is linear, and so that a satisfactory sensitivity may be obtained.

The first step in this calibration is to adjust the distance between the two coils to some arbitrary value. This distance is selected to permit free movement of the armature for the dilation of the specimen. The movable end of the armature is then placed close to the lower coil. An arbitrary voltage is applied to the coils and the circuit is balanced with a potentiometer. The galvanometer mirror is adjusted so that the light beam rests at one end of its permissible travel. The armature is then raised by successive increments, which are indicated on the dial gage, and the position of the light beam of the galvanometer on the drum is noted for each position of the armature. A curve of dilation versus galvanometer light beam position is made. Similar curves are obtained for other field voltages. This procedure is repeated for several distances between the field coils. The results of the calibration are shown in Figure 21. Knowing the approximate dilation of the specimen over the temperature range to be studied and the maximum allowable deflection of the galvanometer, a curve is selected which will give a linear relationship between armature deflection and galvanometer deflection.

Procedure

The specimens for this work were cut from one end of the forged steel bars Table VIII and machined to the required size. They were plated with nickel to a thickness of from 0.005 to 0.010 inch to prevent oxidation.

In making a test, the specimen is placed in the neutral body of commercially pure nickel, and the thermocouple wires inserted in their respective holes. The specimen and neutral body are placed in the furnace and the thermocouple wires connected to the proper instruments. The photographic paper is placed on the drum and calibrated. The furnace is heated to about 850 degrees F. and held at this temperature until the temperature of the specimen attains this value.

The distance between the field coils[*], the armature position, and the field coil voltage[**] are then adjusted

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[*] 0.25 inches

[**] 30 volts

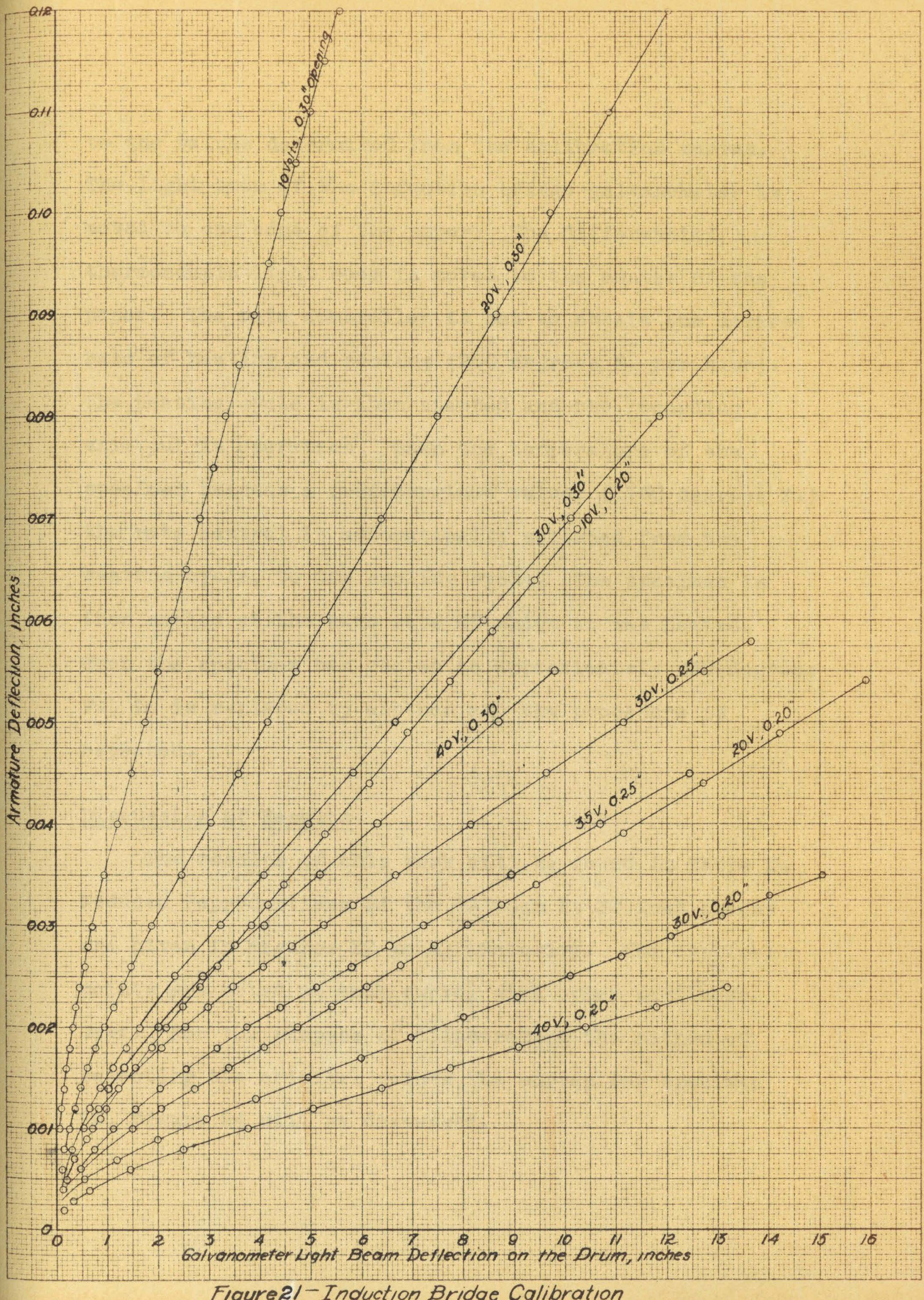


Figure 21 – Induction Bridge Calibration

to the values determined from the calibration curves. The light beam of the induction bridge galvanometer is moved to one edge of the paper. The differential thermocouple light beam is moved to the center of the paper. The rate controller is set to obtain the desired rate of heating and cooling (250 degrees F. per hour). The heating cycle is then started and the recording unit put in operation. When the temperature of the specimen reaches a predetermined value, (1750 degrees F.) the rate control is automatically switched from the heating cycle, to the cooling cycle. The specimen is then cooled at the same rate at which it was heated. When the specimen has cooled to approximately 900 degrees F., it is replaced by another and the procedure is repeated.

Discussion of Results

The results of this work will be found in Table X. Reduced reproductions of the 12 inch by 30 inch charts are given in Figures 22 to 41 inclusive. The critical points are noted on each curve, with other pertinent data. For the purpose of illustrating the method of selecting the critical points the curves for specimen 22, Figure 24 will be discussed.

Table X Thermal Critical Temperatures

Sample	Ac_1, °F.	Ac_3, °F.	Ar_3, °F.	Ar_1, °F.
20	1350	1579	1491	1272
21	1328	1582	1497	1233
22	1336	1583	1500	1240
23	1332	1584	1495	1237
24	1317	1557	1462	1220
25	1324	1577	1484	1231
26	1329	1586	1486	1231
27	1324	1559	1453	1224
28	1324	1562	1455	1233
29	1328	1563	1456	1233

Sample	Ac_1, °F.	Ac_3, °F.	Ar_3, °F.	Ar_1, °F.
30	1348	1488	1403	1264
31	1331	1484	1390	1238
32	1336	1482	1381	1243
33	1337	1479	1380	1241
34	1327	1474	1374	1230
35	1326	1475	1374	1229
36	1330	1485	1388	1233
37	1325	1462	1359	1226
38	1328	1460	1359	1229
39	1326	1463	1373	1230

First, consider the dilation record of the steel. The temperature 1336 degrees F., at which the slope of the heating curve first changes is designated as the Ac_1 point. The Ac_3 temperature, 1584 degrees F., corresponds to the point on the dilation curve at which the slope resumes a relatively constant value. The Ar_3 and Ar_1 temperatures, 1500 degrees F. and 1241 degrees F. respectively, are determined in essentially the same manner from the dilation curve on cooling, but in the reverse order.

Second, consider the differential temperature record of the steel. That temperature, 1336 degrees F., at which the curve on heating deflects sharply to the left is the Ac_1 temperature. The Ac_3 temperature corresponds to that point on the curve at which the slope becomes almost constant, 1582 degrees F. The Ar_3 temperature is that point 1500 degrees F., on the cooling curve at which the first major change of slope is noted. The temperature at which the cooling curve deflects sharply to the left, 1239 degrees F., is designated as the Ar_1 temperature.

Figures 42 and 43 show the effect of copper and silver on the transformation temperatures of SAE 1020

1040 steels. Figures 42A and 43A show that copper up to 1 per cent lowers the critical points of the 0.20 per cent carbon and 0.40 per cent carbon steels. Increasing the copper to 2 per cent has little effect. In preparing the curves which show the effect of the silver on the critical points for steels containing like percentages of copper, the critical temperatures were adjusted to compensate for the varying copper content of the specimens. Figures 42B, C, D, and 43B, C, D show that silver in the presence of copper in the percentages investigated raises both critical temperatures a few degrees. The increase is greater for the A_3 temperature than for the A_1 temperature. The only exception to this statement is the A_3 temperature for the 0.35 per cent carbon steel containing 0.65 per cent copper. Here this critical point is lowered slightly by silver additions.

Conclusions

In this investigation a method has been developed for the graphic determination of thermal critical temperatures. It has been shown that copper in amounts up to 2 per cent lowers the critical temperatures of

SAE 1020 and SAE 1040 steels. Silver in amounts up to 0.25 per cent in the presence of 2 per cent or less of copper has little effect on the critical temperatures of these steels.

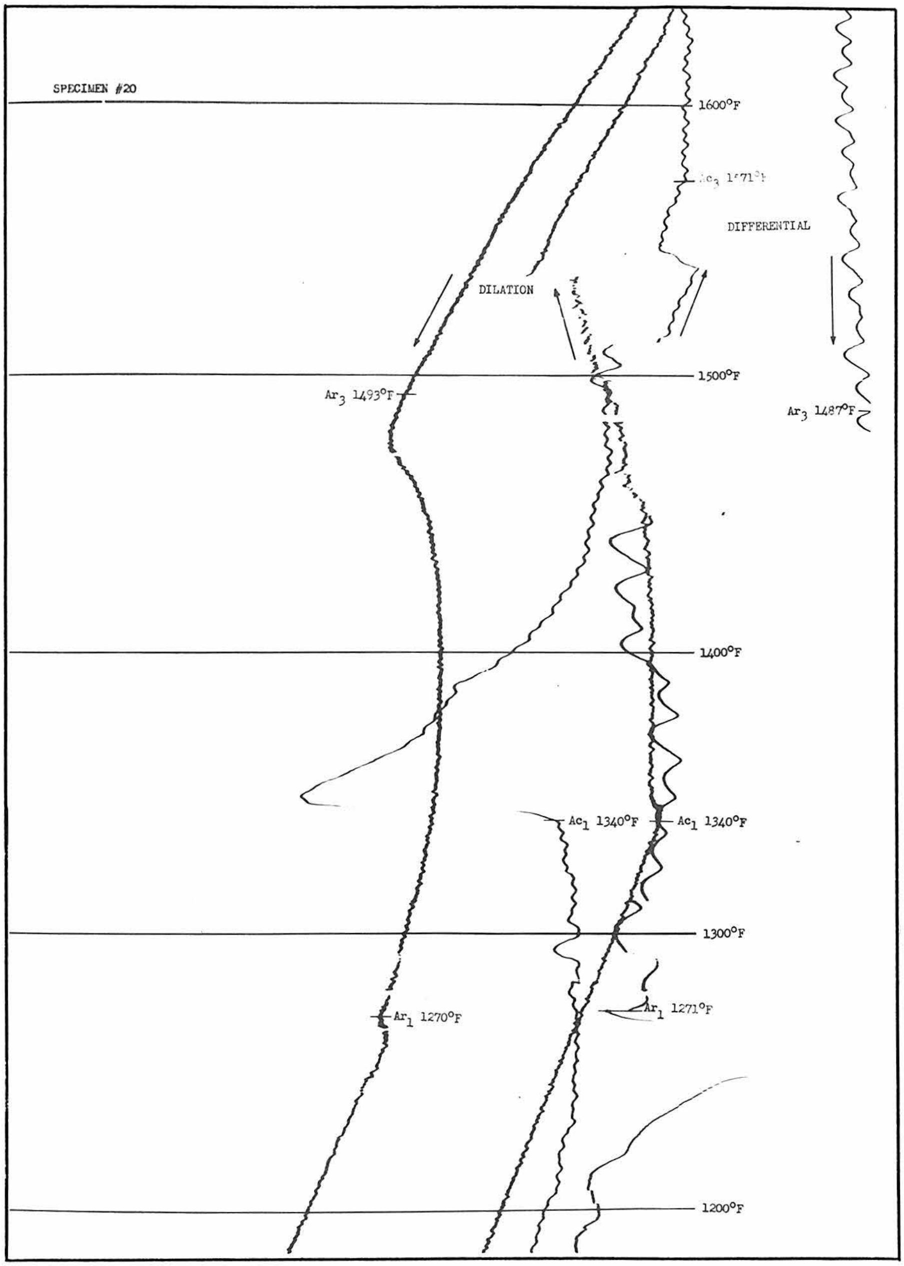


Figure 22.

Specimen 20--Thermal Critical Temperature Chart

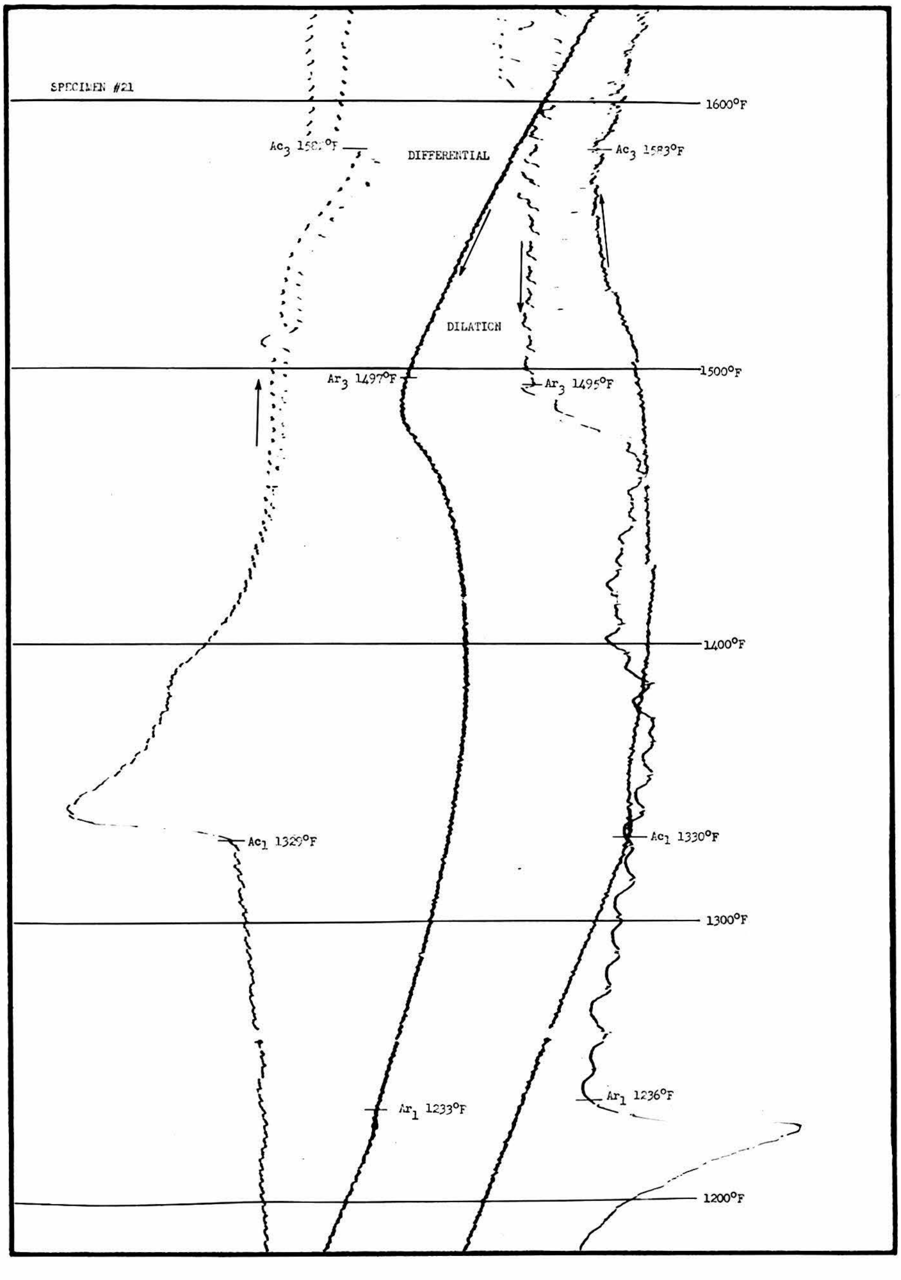


Figure 23.

Specimen 21--Thermal Critical Temperature Chart

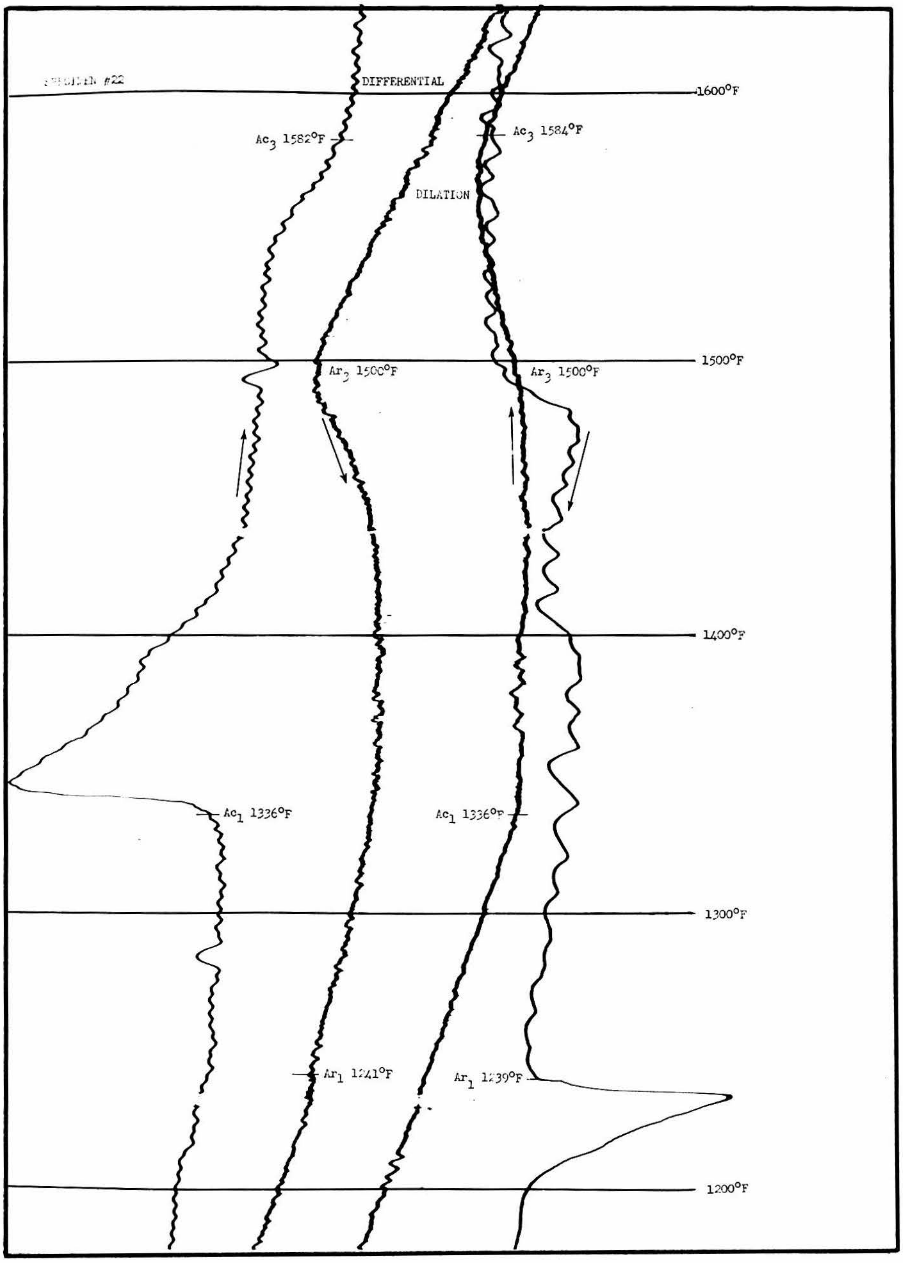


Figure 24.

Specimen 22--Thermal Critical Temperature Chart

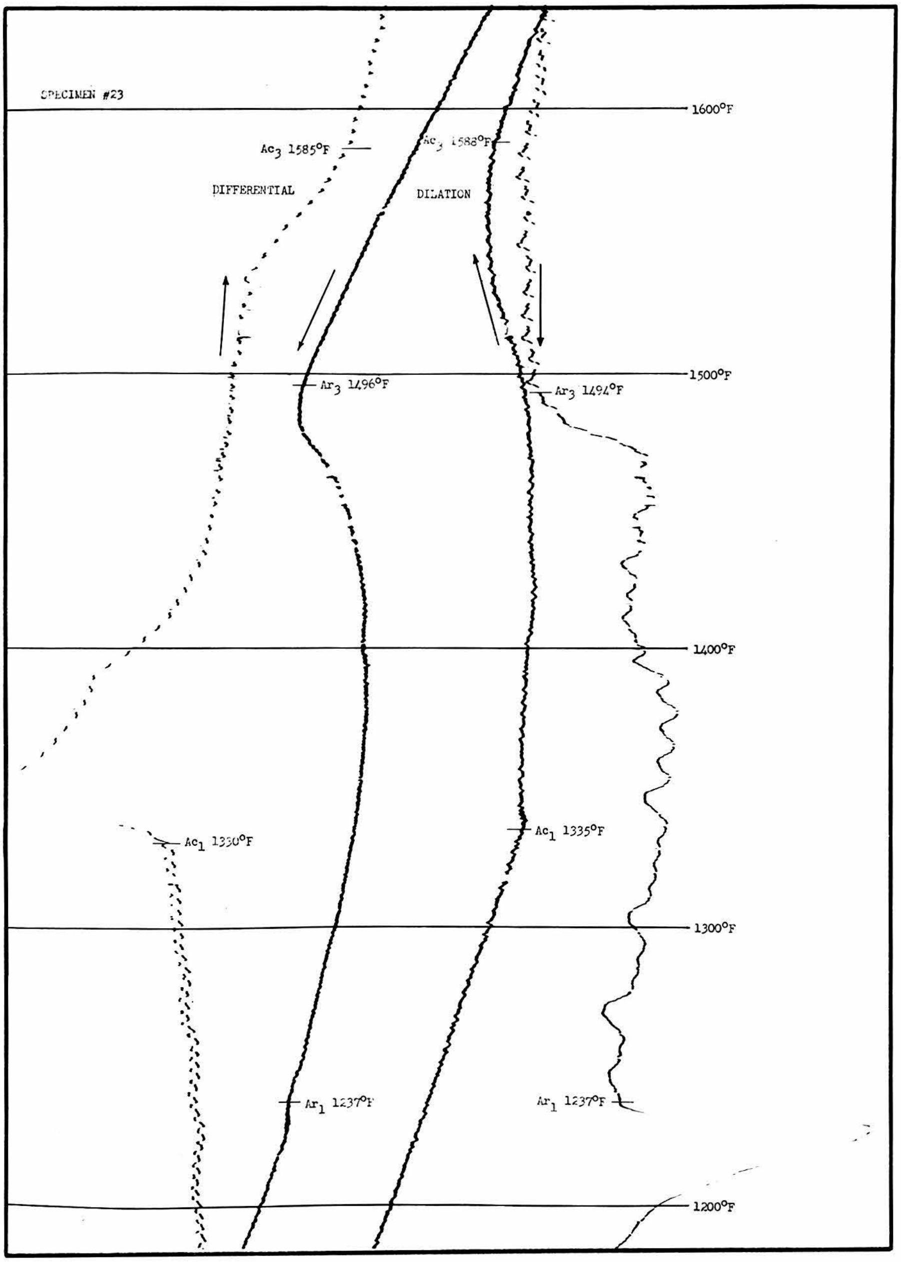


Figure 25.

Specimen 23--Thermal Critical Temperature Chart

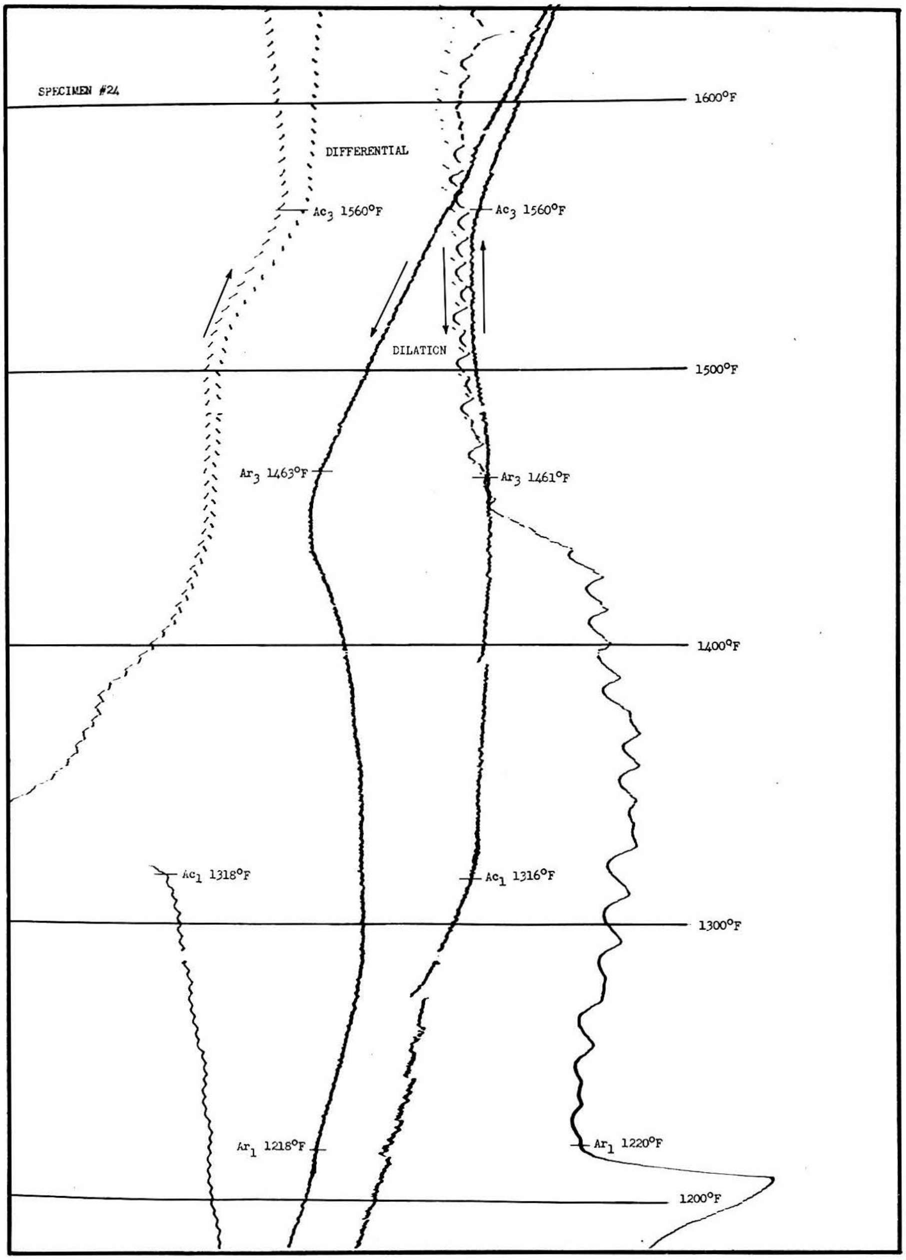


Figure 26.

Specimen 24--Thermal Critical Temperature Chart

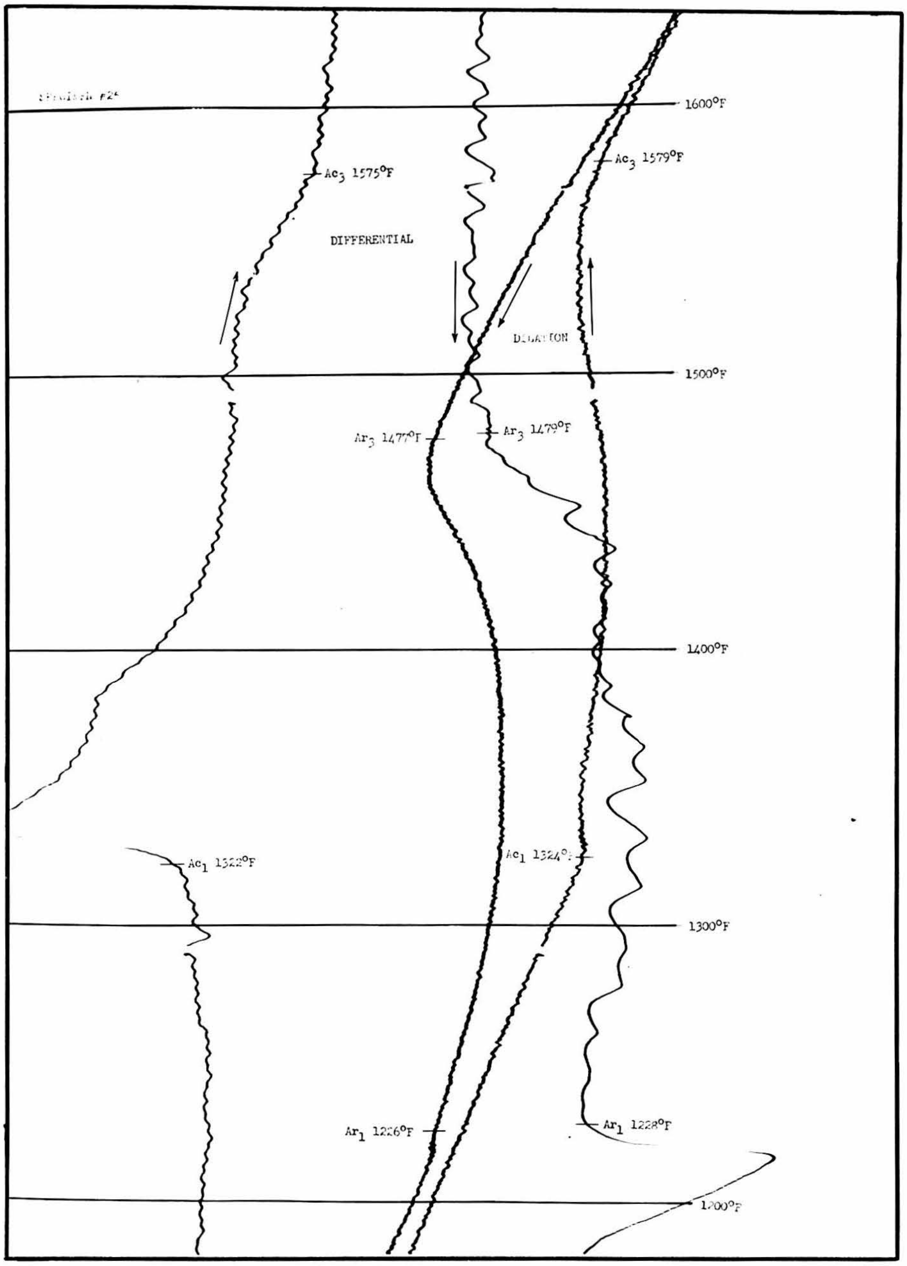


Figure 27.

Specimen 25--Thermal Critical Temperature Chart

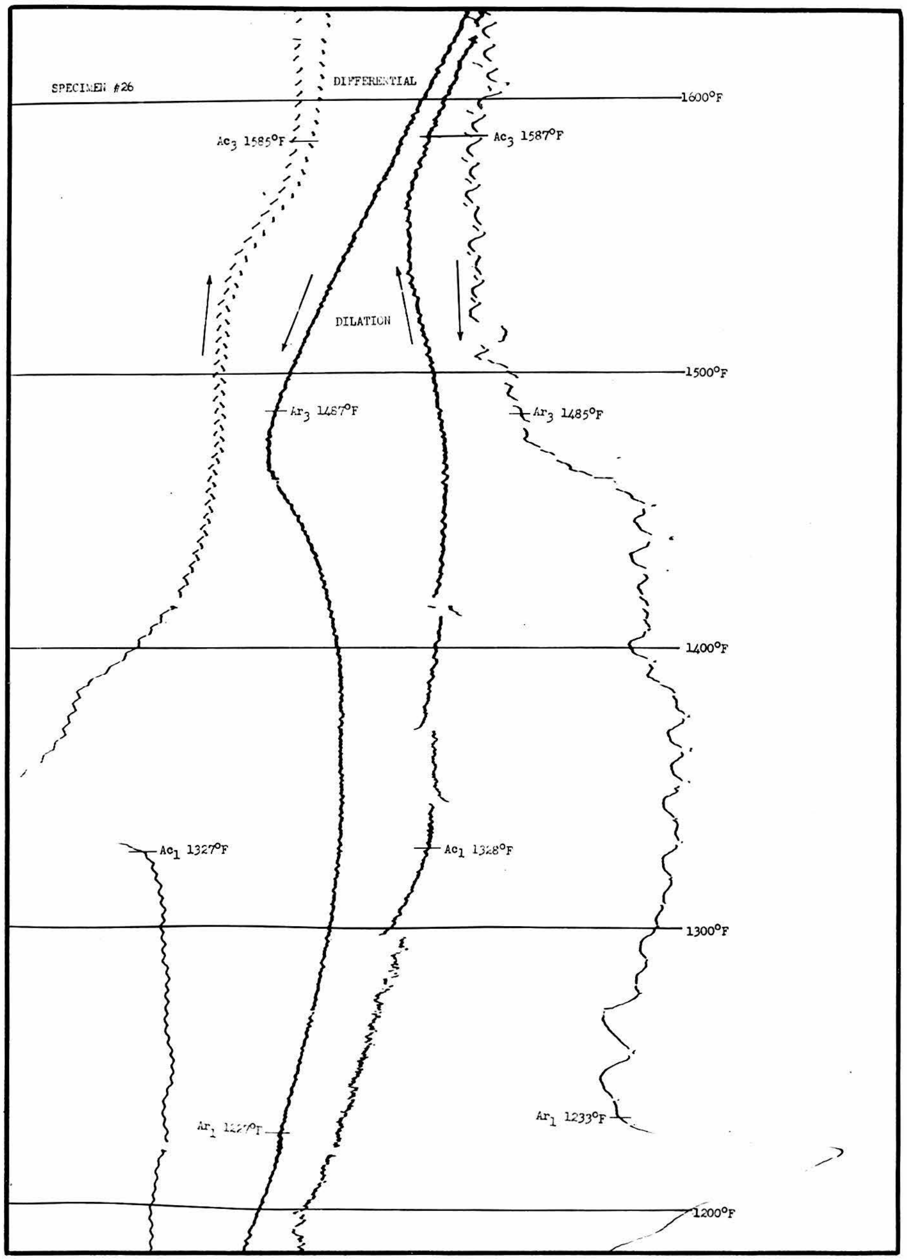


Figure 28.

Specimen 26--Thermal Critical Temperature Chart

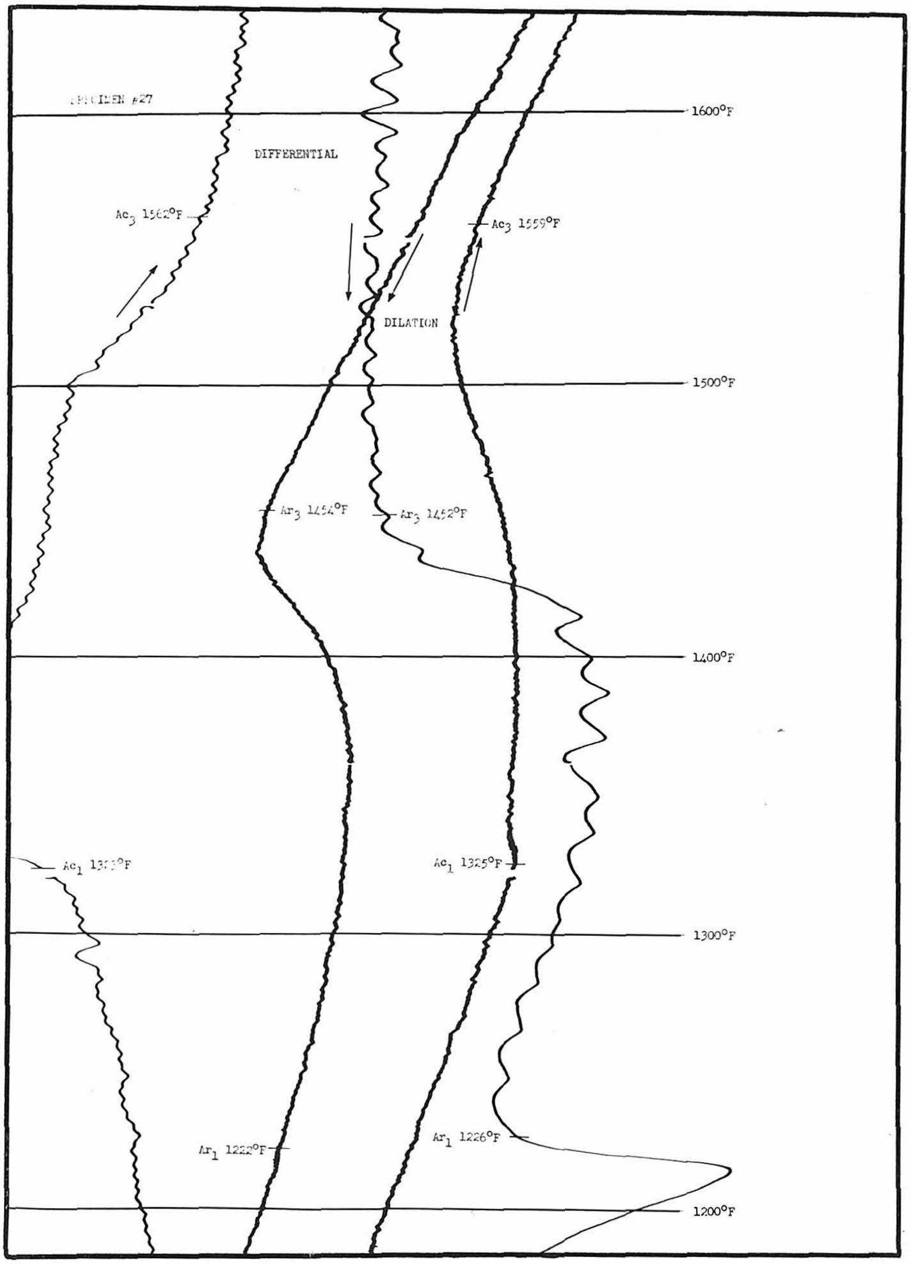


Figure 29.

Specimen 27--Thermal Critical Temperature Chart

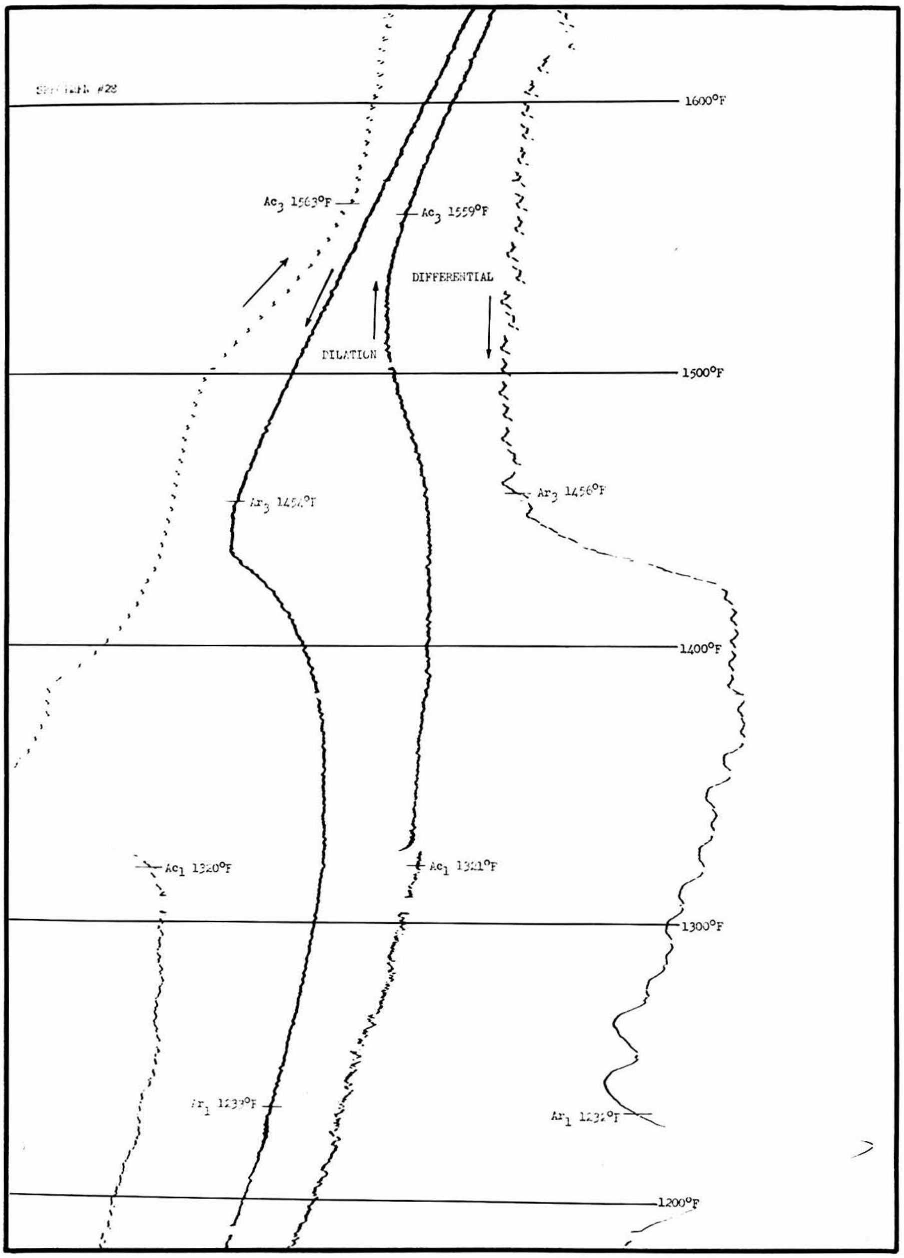


Figure 30.

Specimen 28--Thermal Critical Temperature Chart

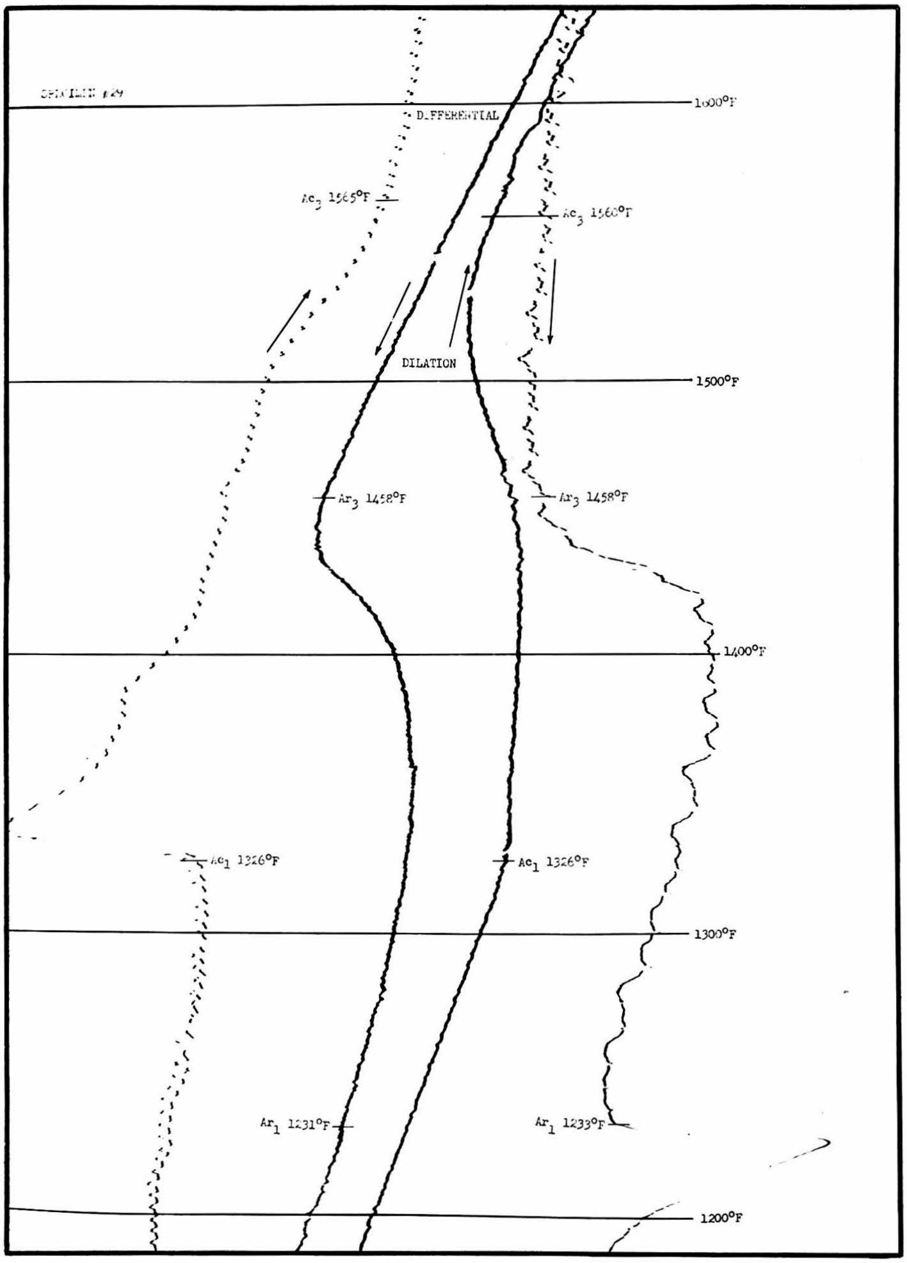


Figure 31.

Specimen 29--Thermal Critical Temperature Chart

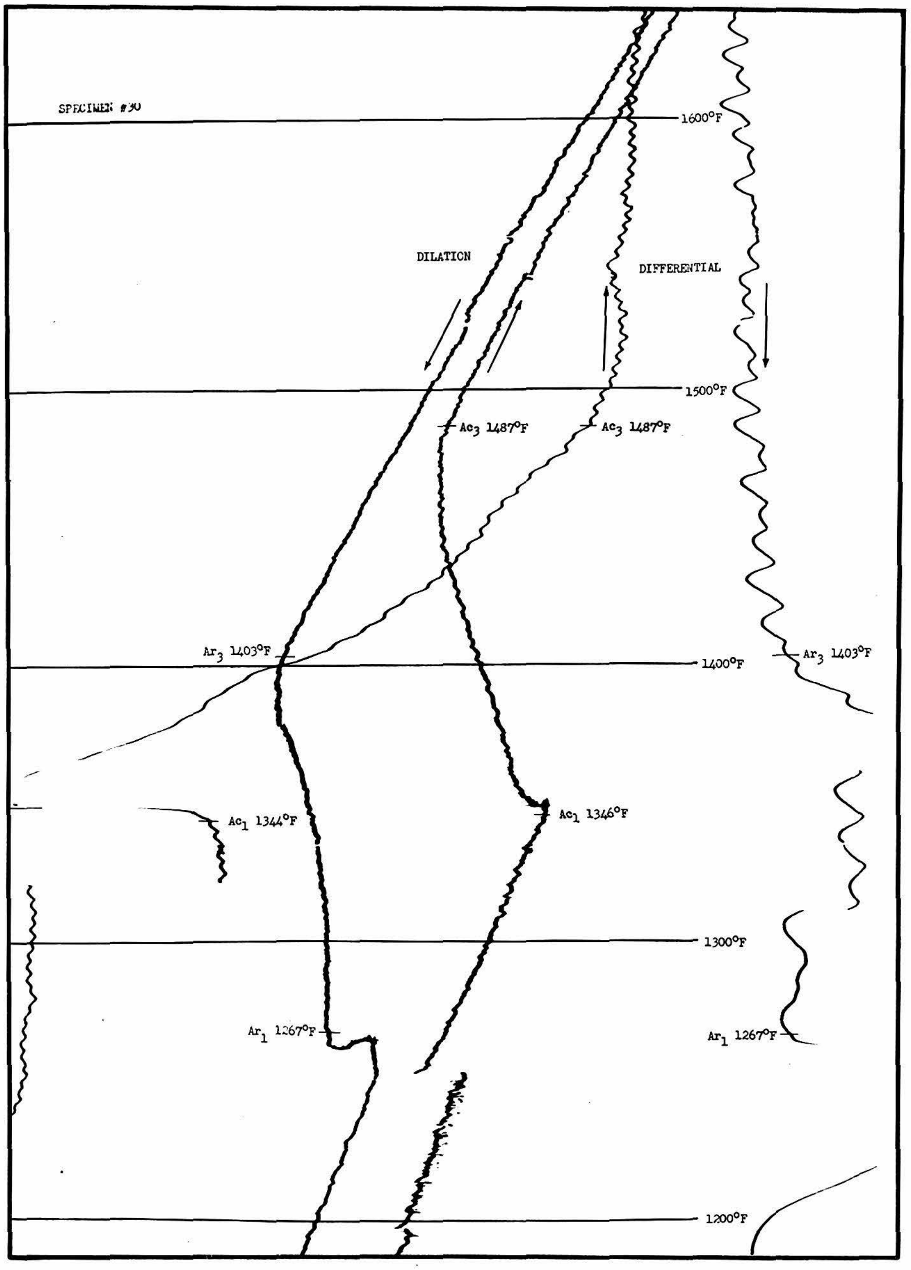


Figure 32.

Specimen 30--Thermal Critical Temperature Chart

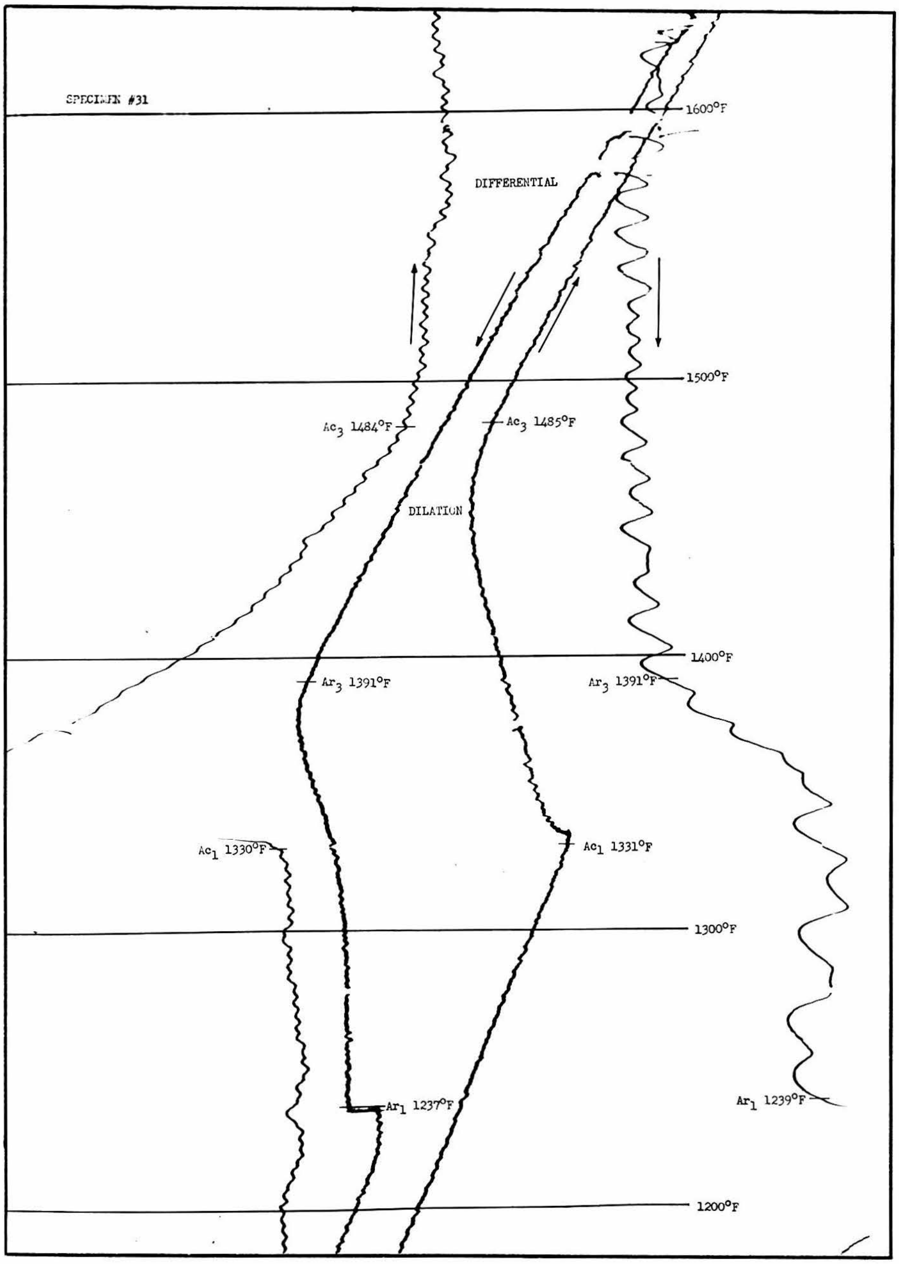


Figure 33.

Specimen 31--Thermal Critical Temperature Chart

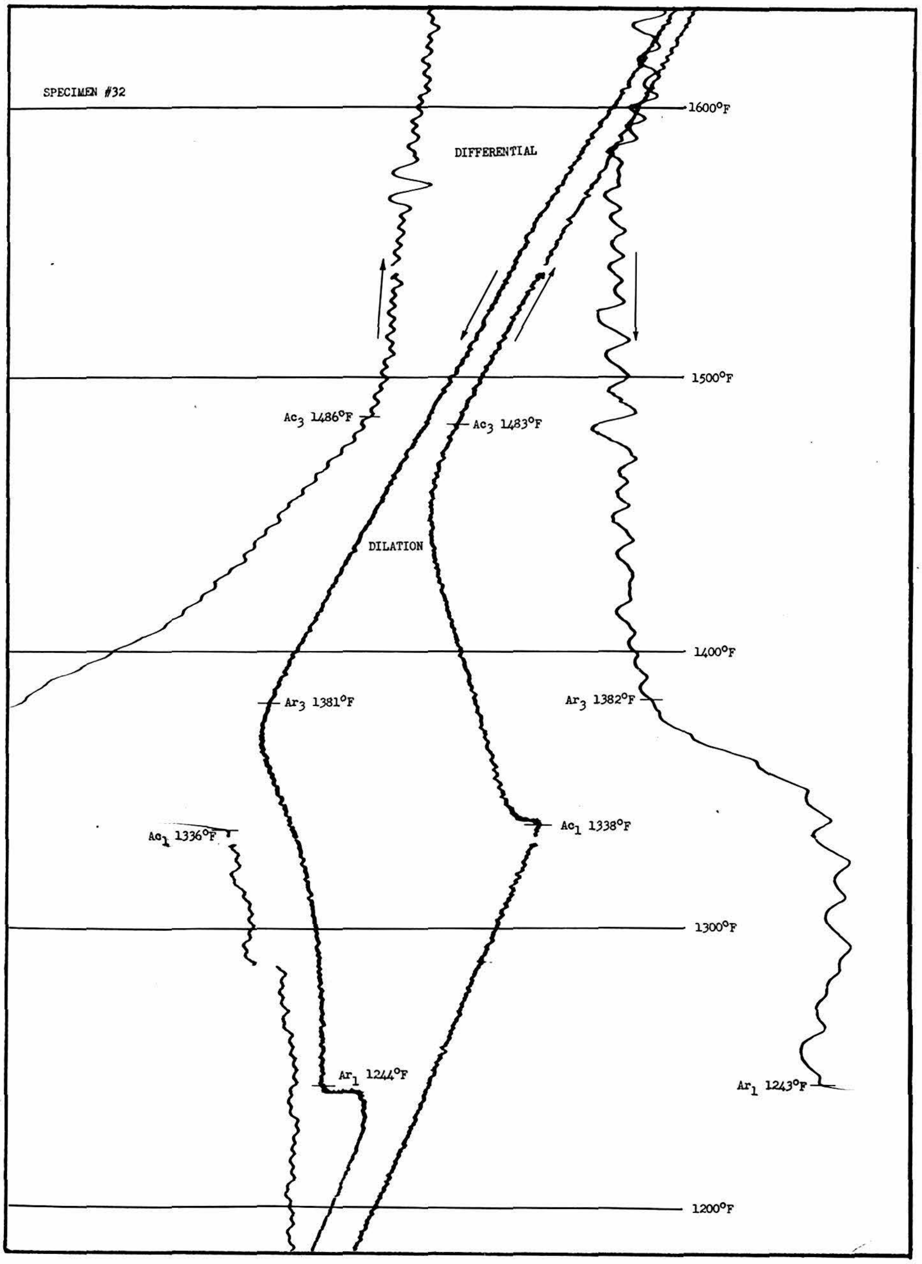


Figure 34.

Specimen 32--Thermal Critical Temperature Chart

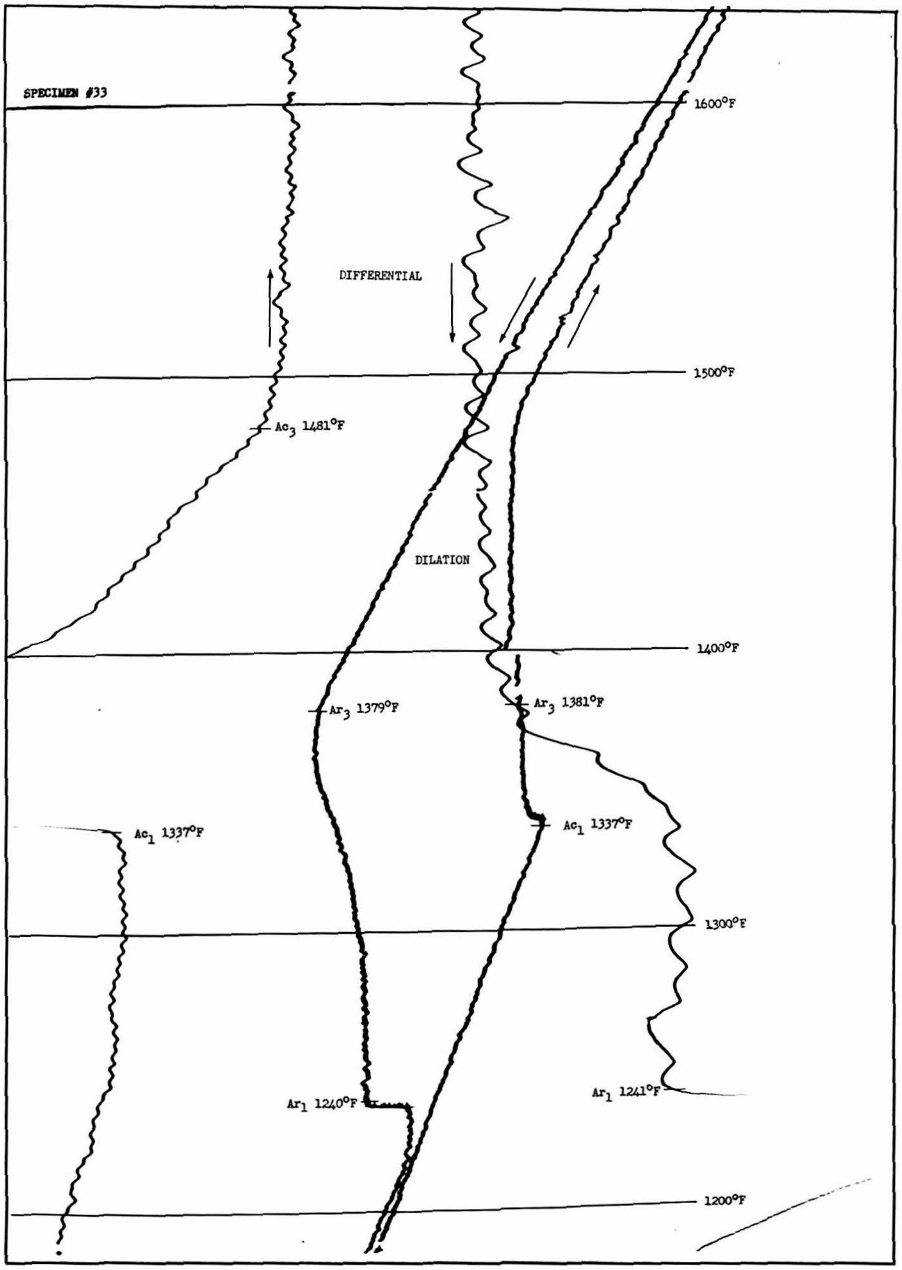


Figure 35.

Specimen 33--Thermal Critical Temperature Chart

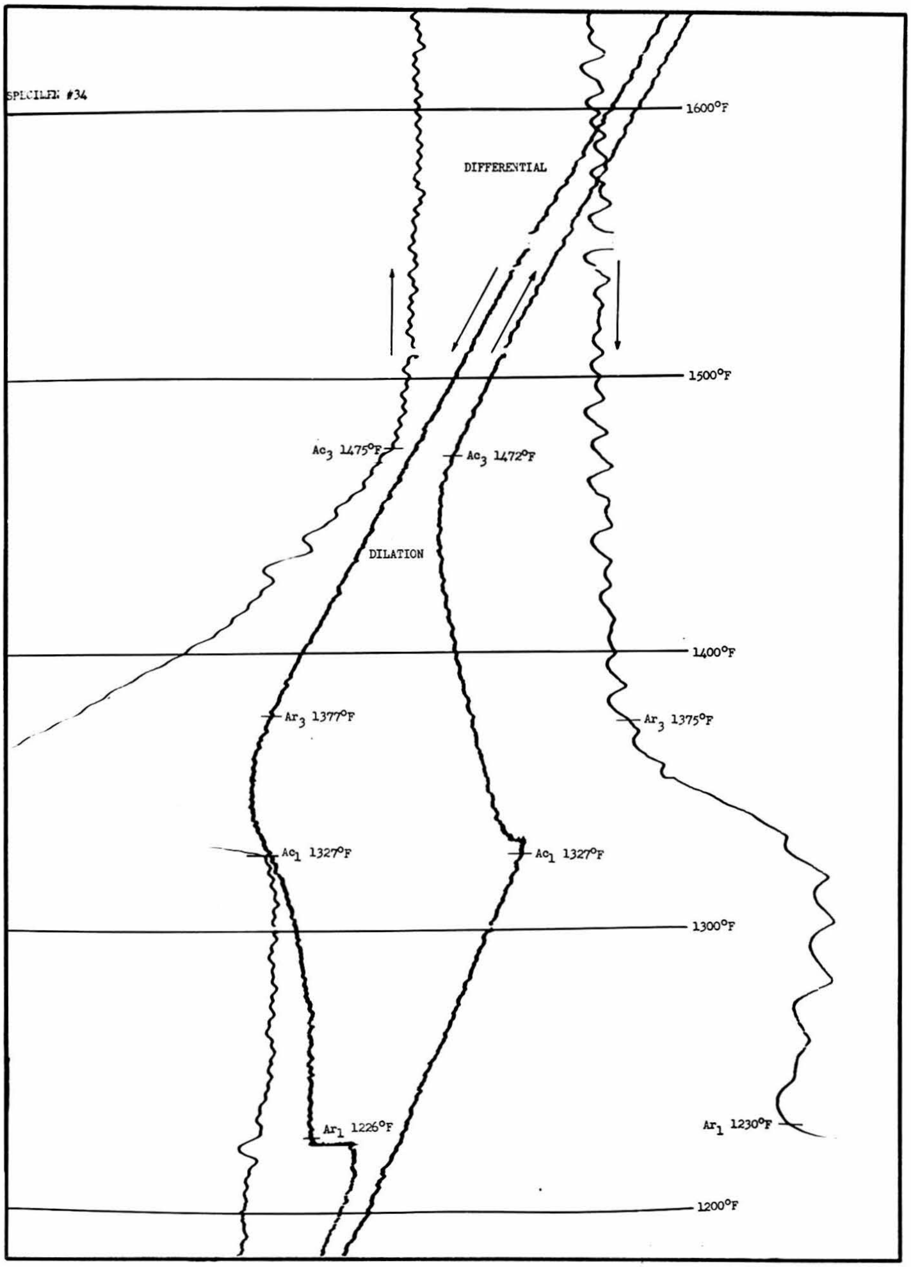


Figure 36.

Specimen 34--Thermal Critical Temperature Chart

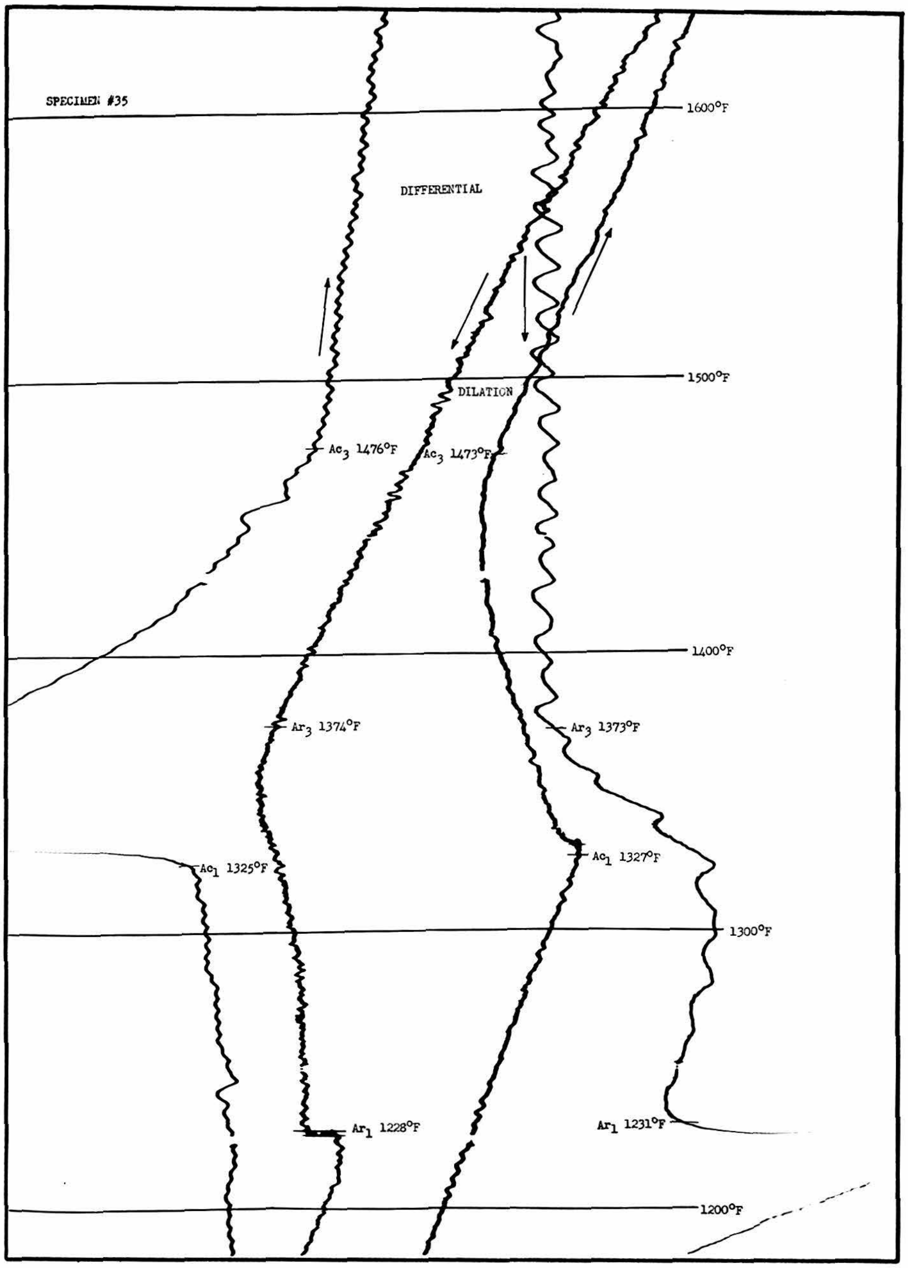


Figure 37.

Specimen 35--Thermal Critical Temperature Chart

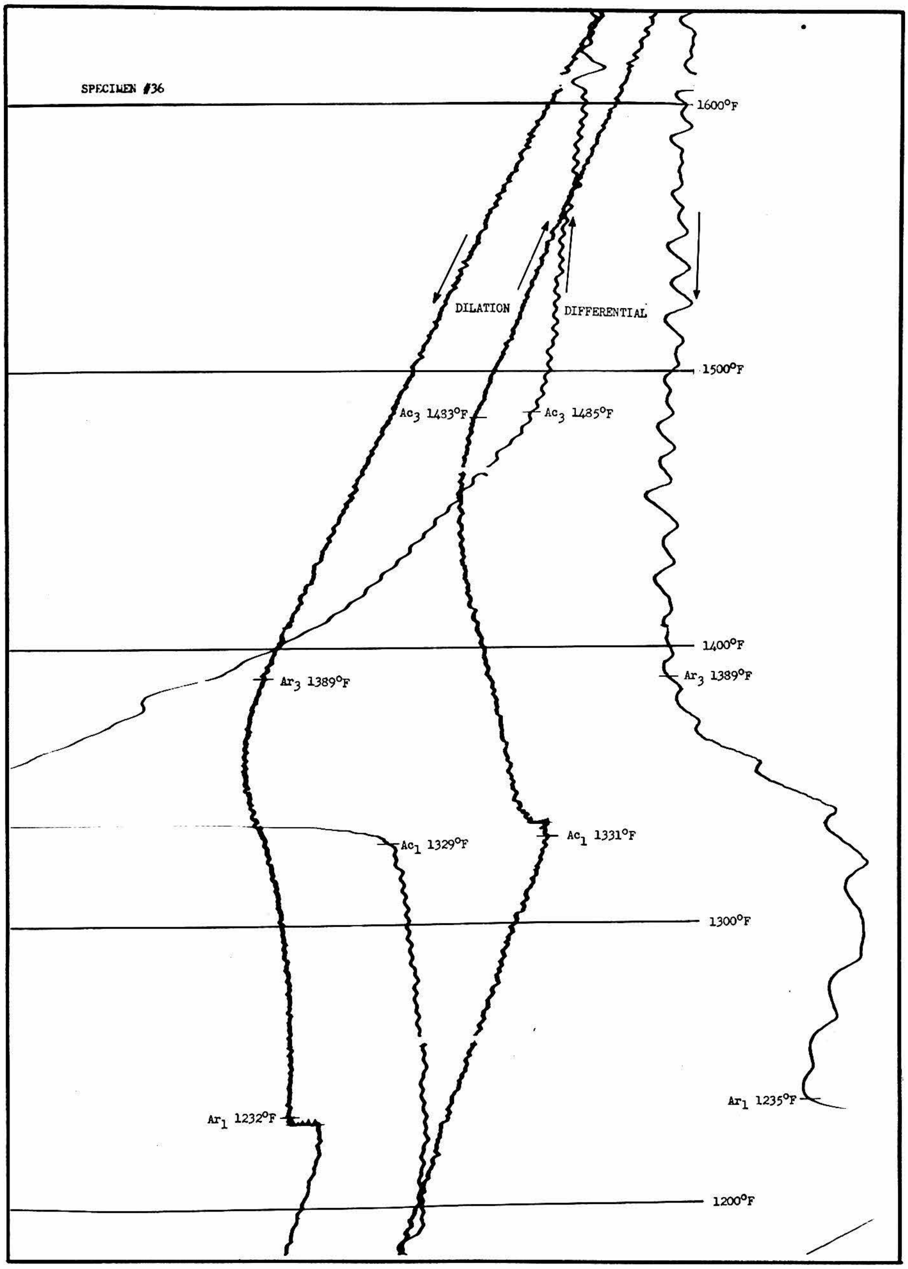


Figure 38.

Specimen 36--Thermal Critical Temperature Chart

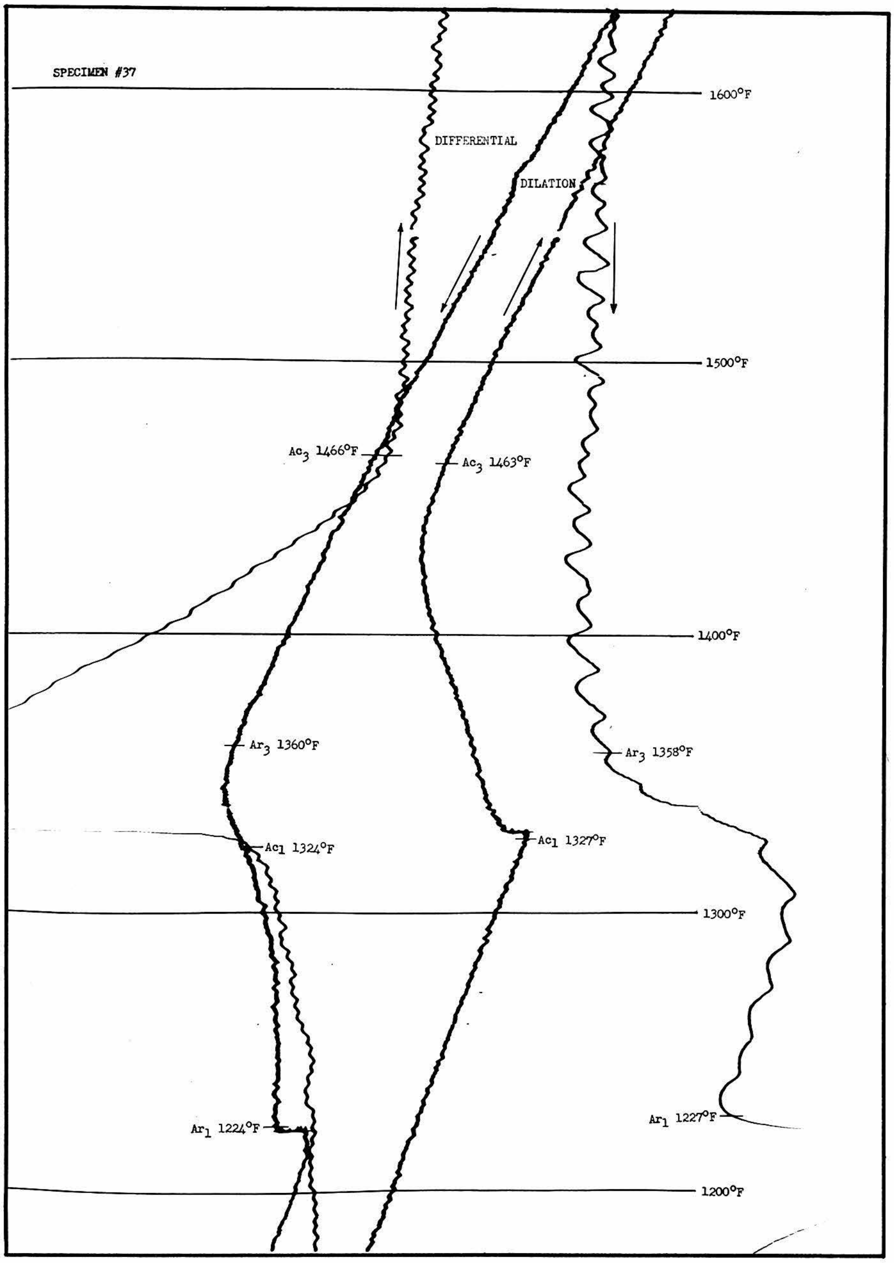


Figure 39.

Specimen 37--Thermal Critical Temperature Chart

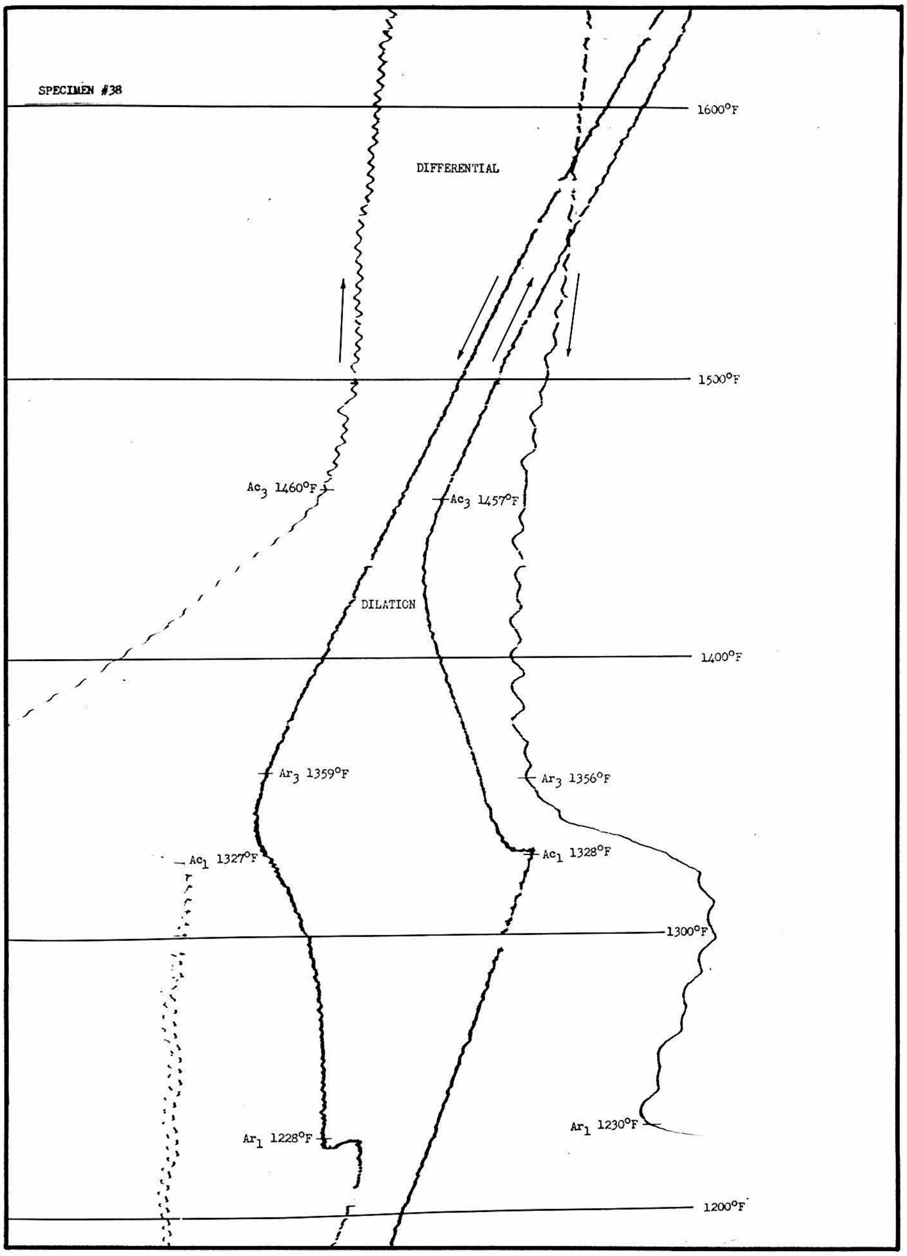


Figure 40.

Specimen 38--Thermal Critical Temperature Chart

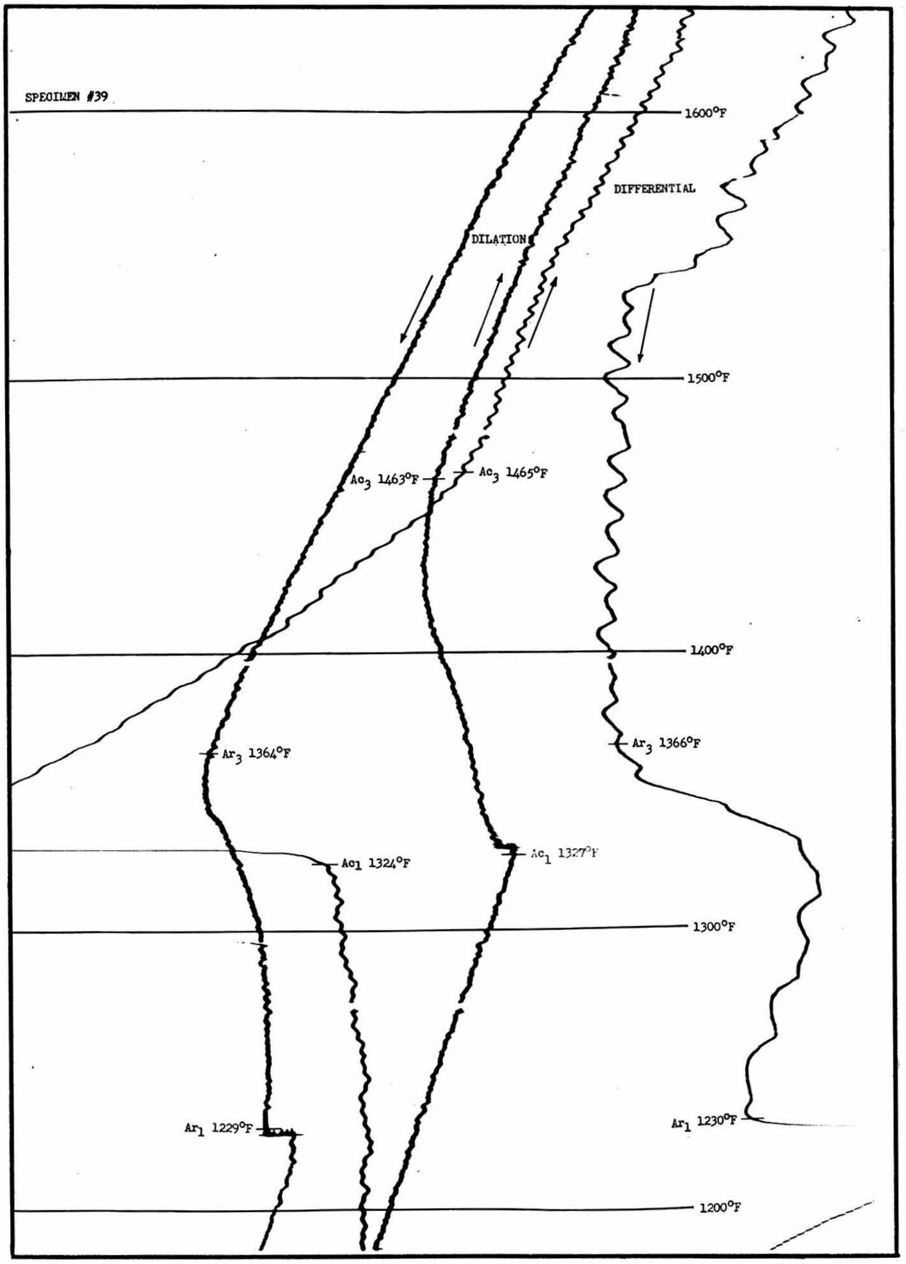
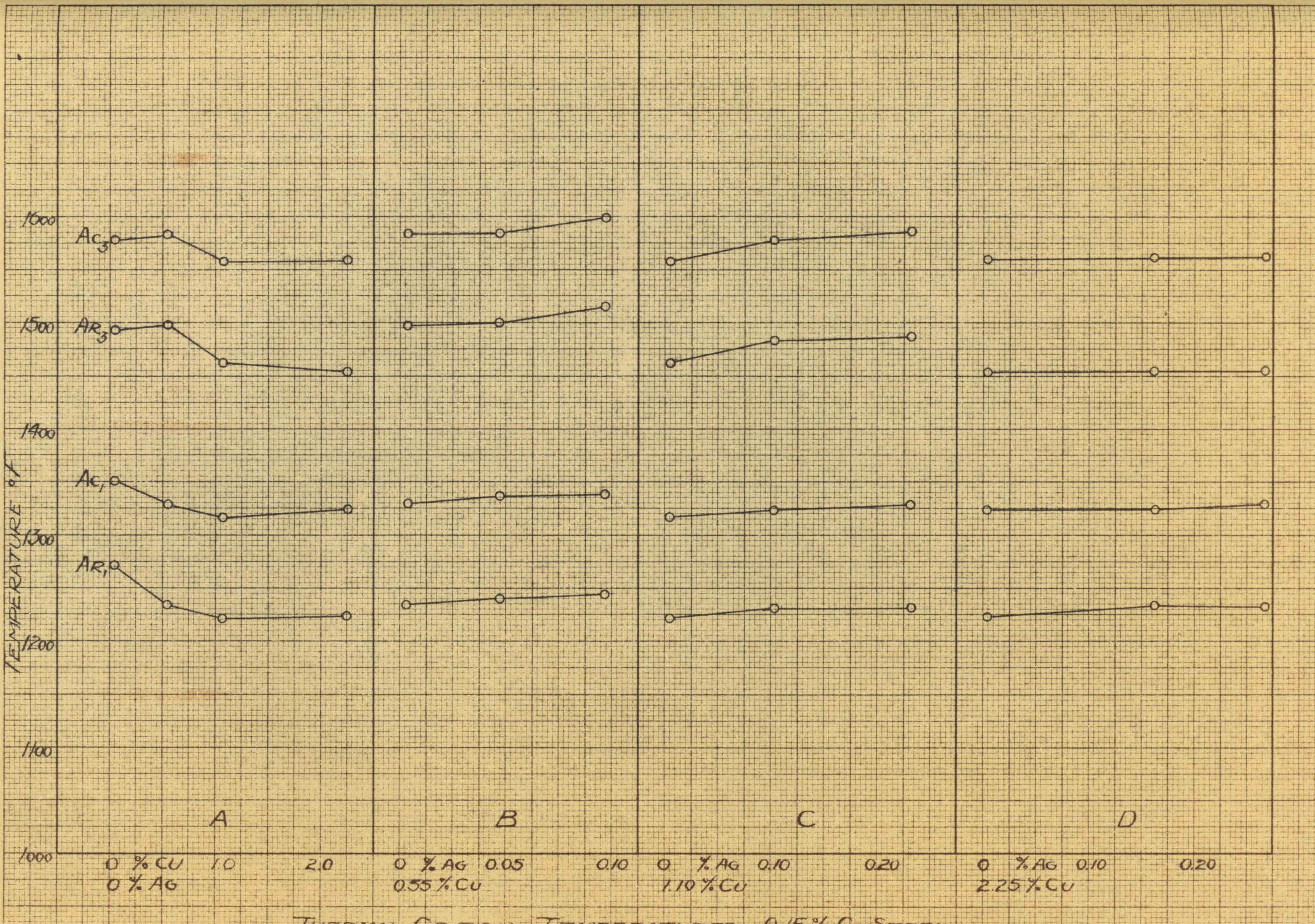
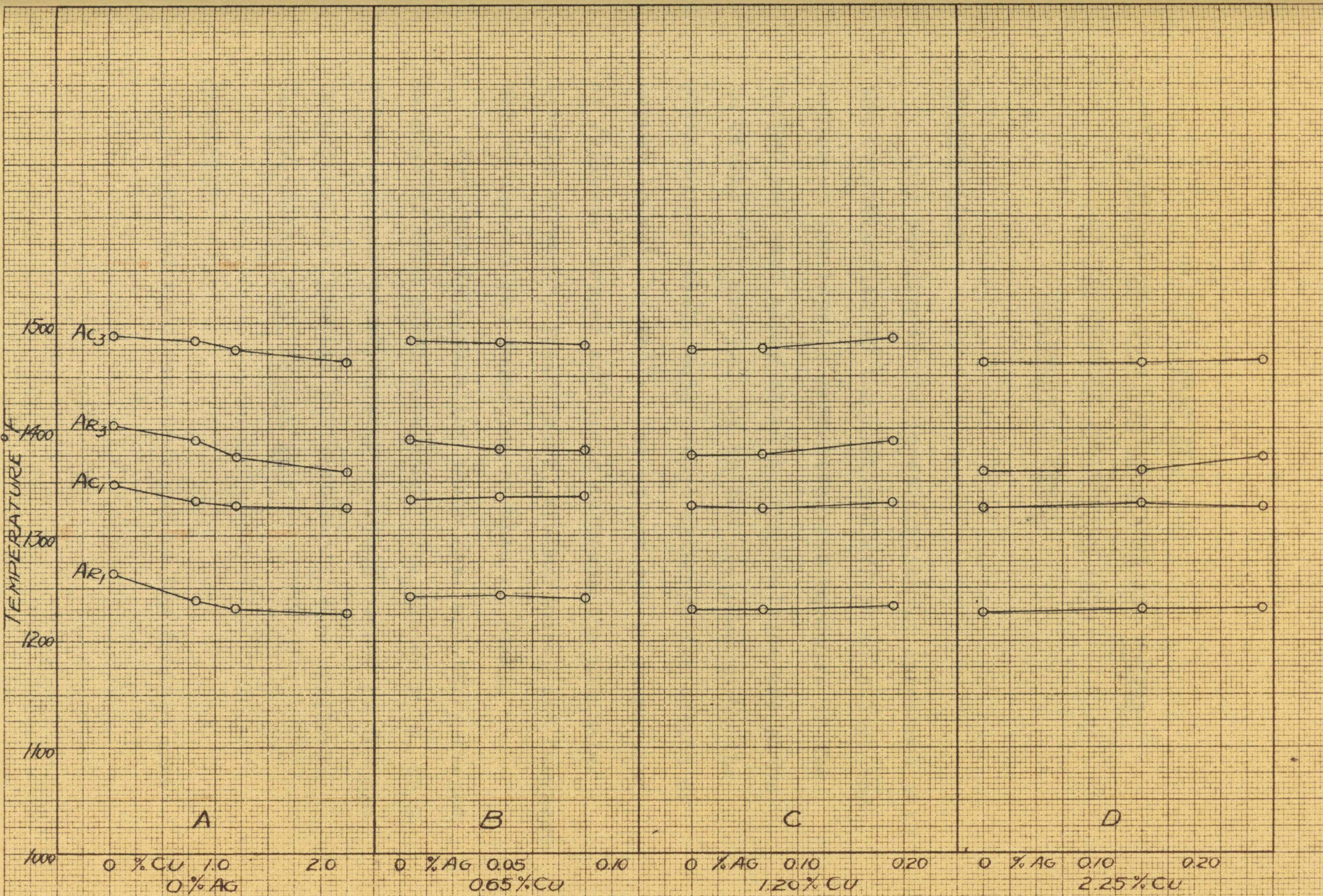


Figure 41.

Specimen 39--Thermal Critical Temperature Chart



THERMAL CRITICAL TEMPERATURES, 0.15 % C STEEL
FIGURE 42



THERMAL CRITICAL TEMPERATURES, 0.35%C STEEL

FIGURE 43

PART IV.

THE EFFECT OF ADDITIONS OF SILVER AND COPPER ON THE TENSILE PROPERTIES AND HARDNESS OF STEEL

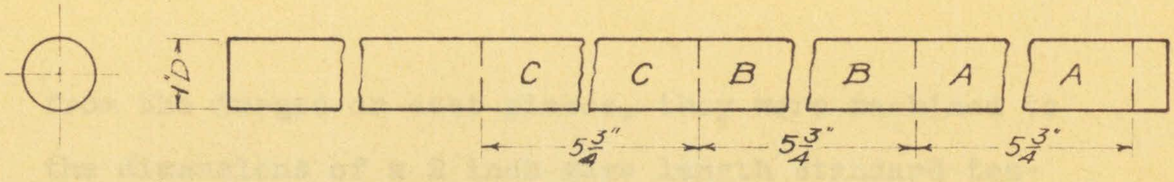
Introduction

This portion of the investigation is concerned with the determination of the combined effect of silver and copper on the tensile properties and hardness of the forged and cast alloy steels. The analyses are given in Tables VIII and IX. As in the previous work, the plain copper steels were tested although the effect of copper is well known[10]. The effect can be summarized as follows: copper additions increase the ultimate tensile strength, yield point, and hardness, and decrease the elongation and reduction of area of steel.

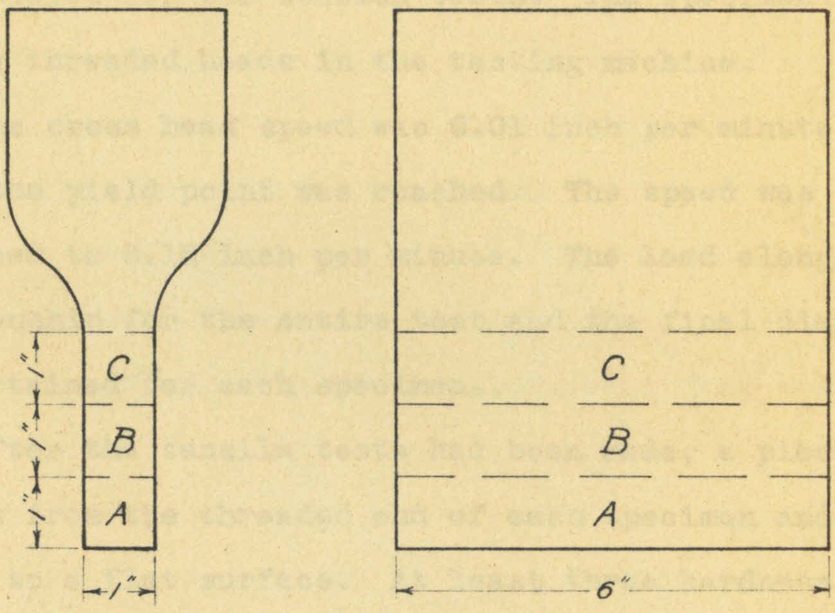
For this determination three cast and three forged samples of each steel were used. The letter A, B, or C which has been added to each specimen number is for the purpose of designating its position in the original casting or forging, Figure 44.

Procedure

After the specimens were cut to the desired size



Forged Specimens



Cast Specimens

Figure 44

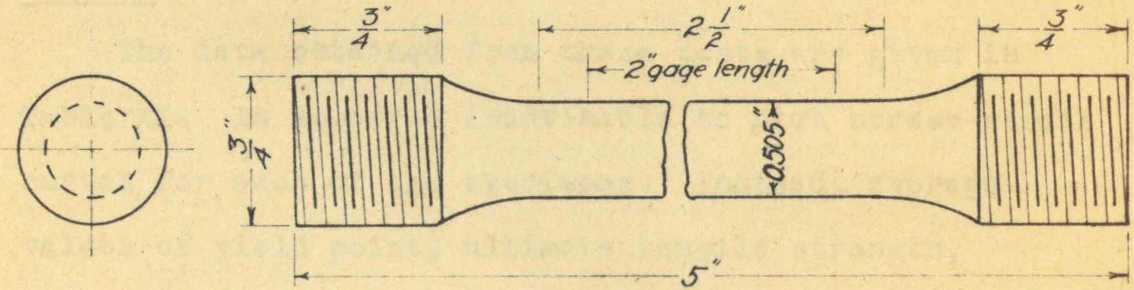


Figure 45—Tensile Test Specimen

from the forged or cast pieces, they were machined to the dimensions of a 2 inch gage length standard tension specimen as shown in Figure 45.

A 30,000 pound Riehle Universal Testing Machine was employed for the tension tests. The specimen was held by threaded heads in the testing machine.

The cross head speed was 0.01 inch per minute until the yield point was reached. The speed was then increased to 0.15 inch per minute. The load elongation relationship for the entire test and the final diameter were obtained for each specimen.

After the tensile tests had been made, a piece was cut from the threaded end of each specimen and ground to a flat surface. At least three hardness determinations were made on each piece with a Rockwell Superficial Hardness Tester.

Results

The data obtained from these tests are given in Table XI. It appeared inadvisable to plot stress-strain curves for each of the specimens. Instead, average values of yield point, ultimate tensile strength, elongation, reduction of area, and hardness for each set of specimens were calculated. These data are given in Tables XII and XIII.

The results of the tests on the forged steels are shown graphically in Figures 46 and 47. Figures 46A and 47A show that copper increases the yield point, ultimate tensile strength and hardness, and decreases the elongation and reduction of area of the 0.15 per cent carbon and 0.35 carbon forged steels. This is in agreement with results obtained by other investigators.

The results of mechanical tests on the steels containing both silver and copper (Figures 46B, C, D and 47B, C, D) are very erratic. Consequently it is impossible to reach any accurate conclusion in this case. However, in no case did the properties show any marked increase or decrease with the silver additions.

One factor which must be considered in interpreting these curves is the variation of the analyses of the different steels. Reference to Table VIII will show that the amounts of all the elements which were found in the samples vary over a range which is sufficient to alter the values of all of the properties tested. An attempt was made to compensate for these variations, but sufficient accurate data were not available. The values obtained from the tests were therefore plotted against the copper and silver contents of the steels without compensation for the variation in the amounts of other elements.

No attempt was made to plot the relation between the properties and the composition of the cast specimens. The original data is in Table XI and the average values of the properties are given in Table XIII. Marked segregation was found in the samples and therefore the analyses obtained were good for only those portions of the specimens analysed.

TABLE XI

ORIGINAL DATA, MECHANICAL PROPERTIES

Spec. No.	D_1	D_2	A_1	A_2	L_2	Load at Yield, lb.	Load at Ult., lb.	Yield Pt. lb./in.^{2}	Ult. Ten. Str. lb./in.^{2}	Elong., % in 2"	Red. of Area, %	Hardness R30T
20AF	0.505	0.258	0.2003	0.0522	2.92	8,040	11,210	40,140	55,960	46.0	67.6	56.8
BF	0.504	0.288	0.1995	0.0651	2.92	6,930	11,220	34,730	56,230	46.0	67.3	58.1
CF	0.505	0.290	0.2003	0.0660	2.84	6,940	11,300	34,640	56,410	42.0	67.0	59.0
21AF	0.504	0.275	0.1995	0.0593	2.79	7,900	11,740	39,600	58,840	39.5	70.2	60.5
BF	0.488	0.264	0.1870	0.0547	2.85	7,760	10,540	41,490	56,360	42.5	70.7	60.3
CF	0.505	0.276	0.2003	0.0598	2.84	8,120	11,460	40,530	57,210	42.0	70.1	61.5
22AF	0.5045	0.280	0.1999	0.0615	2.88	8,460	11,840	42,320	59,220	44.0	69.2	63.1
BF	0.5045	0.279	0.1999	0.0611	2.93	9,160	11,770	45,800	58,800	46.5	69.3	61.2
CF	0.505	0.290	0.2003	0.0660	2.85	8,110	11,760	40,500	58,300	42.5	67.1	61.2
23AF	0.505	0.275	0.2003	0.0593	2.85	8,270	11,780	41,280	58,810	42.5	70.3	61.3
BF	0.505	0.279	0.2003	0.0611	2.80	8,530	11,670	42,600	58,200	40.0	69.4	61.4
CF	0.505	0.290	0.2003	0.0660	2.82	8,850	11,630	44,200	58,100	41.0	67.1	60.9
24AF	0.505	0.299	0.2003	0.0702	2.76	10,110	13,340	50,470	66,590	38.0	64.9	65.6
BF	0.505	0.303	0.2003	0.0721	2.58	10,000	13,200	49,900	65,900	29.0	64.0	65.5
CF	0.504	0.299	0.1995	0.0702	2.72	9,880	13,180	49,500	66,000	36.0	64.8	66.0
25AF	0.504	0.280	0.2003	0.0615	2.80	9,720	12,240	48,720	61,350	40.0	69.2	63.7
BF	0.505	0.285	0.2003	0.0637	2.83	9,330	12,360	46,600	61,700	41.5	68.2	63.3
CF	0.504	0.285	0.1995	0.0637	2.85	9,880	12,320	49,500	61,800	42.5	68.2	63.9
26AF	0.505	0.280	0.2003	0.0615	2.84	9,320	12,270	46,530	61,250	42.0	69.2	64.7
BF	0.504	0.284	0.1995	0.0633	2.83	9,960	12,230	49,900	61,400	41.5	68.3	64.7
CF	0.5045	0.295	0.1999	0.0683	2.81	9,210	12,290	46,100	61,400	40.5	65.8	65.4
27AF	0.5045	0.287	0.1999	0.0646	2.80	10,590	12,930	52,970	65,130	40.0	67.7	67.3
BF	0.504	0.293	0.1995	0.0674	2.74	10,600	13,020	53,200	65,200	37.0	66.3	68.3
CF	0.505	0.290	0.2003	0.0660	2.84	10,700	13,050	53,400	65,200	42.0	67.1	68.5
28AF	0.504	0.284	0.1995	0.0633	2.81	9,870	12,540	49,500	62,800	40.5	68.3	64.3
* BF	0.5045	-	0.1999	-	-	9,540	11,880	47,700	59,400	-	-	66.6
CF	0.5045	0.291	0.1999	0.0665	2.78	10,200	12,510	51,000	62,600	39.0	66.7	68.2
** 29AF	0.504	0.353	0.1995	0.0978	2.57	-	12,330	-	61,800	28.5	51.1	65.1
BF	0.504	0.289	0.1995	0.0655	2.81	10,630	12,640	53,300	63,300	40.5	67.2	65.8
CF	0.504	0.285	0.1995	0.0637	2.80	10,830	12,640	54,300	63,400	40.0	68.1	66.8

*Failed outside gage length. **Imperfect specimen.

TABLE XI (continued)

ORIGINAL DATA, MECHANICAL PROPERTIES

Spec. No.	D_1	D_2	A_1	A_2	L_2	Load at Yield, lb.	Load at Ult., lb.	Yield Pt. lb./in.^{2}	Ult. Ten. Str. lb./in.^{2}	Elong. % in 2"	Red. of Area, %	Hardness R30T
20AC	0.504	0.298	0.1995	0.0697	2.83	-	10,550	-	52,800	41.5	65.2	53.4
BC	0.504	0.316	0.1995	0.0784	2.85	6,000	10,600	30,100	53,200	42.5	60.7	53.4
CC	0.503	0.301	0.1987	0.0712	2.89	7,330	10,500	36,890	52,850	44.5	64.2	54.5
21AC	0.5045	0.320	0.1999	0.0804	2.78	7,360	11,490	36,810	57,470	39.0	59.8	60.4
* BC	-	-	-	-	-	-	-	-	-	-	-	59.8
CC	0.505	0.323	0.2003	0.0819	2.75	6,940	11,270	34,640	56,260	37.5	59.1	58.6
22AC	0.504	0.319	0.1995	0.0799	2.80	7,570	11,850	37,940	59,390	40.0	60.	61.4
* BC	-	-	-	-	-	-	-	-	-	-	-	61.7
CC	0.505	0.342	0.2003	0.0918	2.75	8,200	11,680	40,900	58,300	37.5	54.2	60.4
23AC	0.496	0.319	0.1932	0.0799	2.80	7,600	11,370	39,340	58,850	40.0	58.6	61.1
BC	0.505	0.336	0.2003	0.0886	2.75	8,120	11,660	40,700	58,400	37.5	55.7	61.8
* CC	-	-	-	-	-	-	-	-	-	-	-	61.2
24AC	0.5045	0.3160	0.1999	0.0784	2.74	8,710	12,330	43,570	61,670	37.0	60.8	64.2
BC	0.5045	0.352	0.1999	0.0973	2.79	8,460	12,120	42,300	60,600	39.5	52.3	62.7
CC	0.5045	0.324	0.1999	0.0824	2.74	8,560	12,160	42,800	60,800	37.0	58.7	63.4
25AC	0.504	0.311	0.1995	0.0759	2.80	8,770	12,050	43,960	60,390	40.0	61.9	64.2
BC	0.504	0.341	0.1995	0.0913	2.70	9,190	12,190	46,000	61,000	35.0	54.3	64.8
CC	0.504	0.328	0.1995	0.0844	2.77	8,760	12,030	43,800	60,300	38.5	57.6	64.5
26AC	0.503	0.310	0.1987	0.0754	2.72	9,080	12,170	45,700	61,250	36.0	62.0	65.1
BC	0.505	0.324	0.2003	0.0824	2.76	9,330	12,250	46,700	61,200	38.0	59.8	65.4
CC	0.504	0.328	0.1995	0.0844	2.68	9,230	12,190	46,300	61,100	34.0	57.6	66.0
27AC	0.504	0.305	0.1995	0.0730	2.77	10,050	12,790	50,370	64,100	38.5	63.3	67.6
BC	0.504	0.342	0.1995	0.0918	2.62	9,620	12,780	48,200	64,000	31.0	54.0	65.9
CC	0.505	0.343	0.2003	0.0924	2.74	10,130	12,720	50,700	63,500	37.0	53.8	68.5
28AC	0.5035	0.298	0.1991	0.0697	2.74	9,920	12,770	49,800	64,100	37.0	65.0	66.7
BC	0.504	0.311	0.1995	0.0759	2.78	10,580	12,960	53,000	65,000	39.0	62.0	67.6
CC	0.503	0.310	0.1987	0.0754	2.70	10,070	12,600	50,600	63,400	35.0	62.0	67.6
29AC	0.505	0.298	0.2003	0.0697	2.86	9,340	12,580	46,630	62,800	43.0	65.2	65.3
BC	0.504	0.335	0.1995	0.0881	2.74	10,500	12,690	52,700	63,500	37.0	55.8	67.3
CC	0.502	0.335	0.1979	0.0881	2.70	10,140	12,710	51,200	64,300	35.0	55.3	65.4

*Porous specimens

TABLE XI (continued)

ORIGINAL DATA, MECHANICAL PROPERTIES

Spec. No.	D_1	D_2	A_1	A_2	L_2	Load at Yield, lb.	Load at Ult., lb.	Yield Pt. lb./in.^{2}	Ult. Ten. Str. lb./in.^{2}	Elong. % in 2"	Red. of Area, %	Hardness R30T
30AF	0.5045	0.333	0.1999	0.0870	2.72	9,488	14,950	47,400	74,750	36.0	56.4	68.2
BF	0.505	0.330	0.2003	0.0855	2.74	9,860	14,880	49,300	74,200	37.0	57.3	66.9
CF	0.505	0.328	0.2003	0.0844	2.74	9,760	15,010	48,700	75,000	37.0	57.8	66.2
31AF	0.5045	0.355	0.1999	0.0989	2.66	10,390	15,540	51,900	77,700	33.0	50.5	69.1
BF	0.504	0.335	0.1995	0.0881	2.69	10,380	15,500	51,900	77,700	34.5	55.8	69.6
CF	0.505	0.334	0.2003	0.0876	2.75	10,800	15,720	53,800	78,500	37.5	56.3	69.2
32AF	0.505	0.343	0.2003	0.0924	2.76	10,400	15,590	51,800	77,750	38.0	53.8	68.5
BF	0.505	0.333	0.2003	0.0870	2.67	10,610	15,430	53,000	77,100	33.5	56.6	68.8
CF	0.504	0.339	0.1995	0.0902	2.64	10,600	15,540	53,200	77,900	32.0	54.7	68.8
33AF	0.505	0.380	0.2003	0.1134	2.66	10,340	15,740	51,700	78,600	33.0	43.3	70.2
BF	0.503	0.335	0.1987	0.0881	2.67	10,780	15,510	54,300	78,100	33.5	55.7	69.3
CF	0.505	0.341	0.2003	0.0913	2.70	10,430	15,740	52,200	78,500	35.0	54.6	69.5
34AF	0.505	0.342	0.2003	0.0918	2.66	11,310	16,190	56,500	80,800	33.0	54.7	72.6
BF	0.505	0.358	0.2003	0.1006	2.62	11,770	15,920	58,700	79,500	31.0	49.8	70.0
CF	0.504	0.337	0.1995	0.0891	2.69	11,690	16,110	58,600	80,800	34.5	55.3	71.0
35AF	0.5045	0.325	0.1999	0.0829	2.70	11,450	15,860	57,300	79,300	35.0	58.6	72.5
BF	0.505	0.331	0.2003	0.0860	2.67	12,630	15,820	63,100	79,000	33.5	57.0	72.4
CF	0.5045	0.353	0.1999	0.0978	2.68	11,700	15,920	58,500	79,700	34.0	51.1	71.4
36AF	0.504	0.326	0.1995	0.0834	2.65	11,680	15,780	58,500	79,000	32.5	58.2	70.2
BF	0.504	0.326	0.1995	0.0834	2.71	11,450	15,600	57,400	78,200	35.5	58.2	71.5
CF	0.505	0.334	0.2003	0.0876	2.64	11,610	16,690	58,000	78,200	32.0	56.2	70.9
37AF	0.5045	0.328	0.1999	0.0844	2.63	13,150	16,890	65,800	84,500	31.5	57.7	73.5
BF	0.505	0.338	0.2003	0.0897	2.59	13,060	16,530	65,200	82,500	29.5	55.2	72.5
CF	0.504	0.335	0.1995	0.0881	2.65	12,750	16,490	63,800	82,600	32.5	55.8	72.8
38AF	0.5035	0.324	0.1991	0.0824	2.68	12,760	16,720	64,000	83,900	34.0	58.7	74.4
BF	0.505	0.332	0.2003	0.0865	2.62	13,200	16,640	65,800	83,100	31.0	56.8	73.1
CF	0.505	0.341	0.2003	0.0913	2.59	12,680	16,480	63,200	82,200	29.5	54.4	72.3
39AF	0.504	0.328	0.1995	0.0844	2.65	12,610	16,090	63,200	80,600	32.5	57.7	73.1
BF	0.505	0.339	0.2003	0.0902	2.63	12,570	15,850	62,800	79,200	31.5	54.8	70.3
CF	0.5045	0.345	0.1999	0.0934	2.63	11,930	15,840	59,700	79,300	31.5	53.3	70.8

TABLE XI (continued)

ORIGINAL DATA, MECHANICAL PROPERTIES

Spec. No.	D_1	D_2	A_1	A_2	L_2	Load at Yield, lb.	Load at Ult., lb.	Yield Pt. lb./in.^{2}	Ult. Ten. Str. lb./in.^{2}	Elong., % in 2"	Red. of Area, %	Hardness R30T
30AC	0.504	0.393	0.1995	0.1213	2.64	9,010	14,690	45,160	73,630	32.0	39.2	67.2
BC	0.503	0.424	0.1987	0.1411	2.56	9,540	14,790	48,000	74,400	28.0	28.8	69.1
CC	0.5045	0.406	0.1999	0.1294	2.56	9,250	14,650	46,200	73,300	28.0	35.2	66.3
31AC	0.505	0.402	0.2003	0.1269	2.58	10,520	15,490	52,600	77,400	29.0	36.8	70.5
BC	0.504	0.421	0.1995	0.1392	2.58	11,270	15,530	56,400	77,800	29.0	30.4	70.3
CC	0.503	0.415	0.1987	0.1352	2.50	10,730	15,420	54,000	77,800	25.0	31.1	69.7
32AC	0.504	0.406	0.1995	0.1294	2.58	10,420	15,420	52,300	77,300	29.0	35.3	71.3
BC	0.503	0.444	0.1987	0.1548	2.38	10,960	15,380	55,200	77,300	19.0	22.0	71.2
CC	0.503	0.416	0.1987	0.1359	2.48	10,580	15,110	53,200	76,100	24.0	31.9	71.2
33AC	0.504	0.391	0.1995	0.1200	2.59	9,650	14,380	48,300	72,100	29.5	39.8	68.1
BC	0.504	0.431	0.1995	0.1458	2.47	10,090	14,290	50,600	71,600	23.5	26.8	67.3
CC	0.5035	0.447	0.1991	0.1569	2.46	10,290	14,130	51,600	71,000	23.0	21.3	67.8
34AC	0.504	0.396	0.1995	0.1231	2.56	11,340	16,000	56,840	80,190	28.0	38.2	72.0
BC	0.504	0.440	0.1995	0.1520	2.44	12,020	15,990	60,200	80,000	22.0	23.8	72.1
CC	0.503	0.4250	0.1987	0.1418	2.46	12,060	15,840	60,700	79,700	23.0	28.6	72.3
35AC	0.5055	0.416	0.2007	0.1359	2.63	11,370	15,760	56,600	78,500	31.5	32.3	72.5
BC	0.505	0.443	0.2003	0.1541	2.46	11,250	15,690	56,200	78,300	23.0	23.1	73.3
CC	0.504	0.456	0.1995	0.1633	2.35	11,410	15,470	57,200	77,500	17.5	18.4	72.4
36AC	0.504	0.399	0.1995	0.1250	2.61	11,390	15,650	57,090	78,440	30.5	37.4	70.9
BC	0.504	0.446	0.1995	0.1562	2.37	11,620	15,680	58,300	78,500	18.5	21.8	70.9
CC	0.505	0.432	0.2003	0.1465	2.50	11,660	15,420	58,200	77,000	25.0	26.8	70.9
37AC	0.504	0.402	0.1995	0.1269	2.57	12,490	16,520	62,600	82,800	28.5	36.4	72.4
BC	0.504	0.437	0.1995	0.1499	2.40	12,790	16,650	64,000	83,500	20.0	24.9	75.1
CC	0.504	0.428	0.1995	0.1438	2.46	12,690	16,410	63,500	82,300	23.0	27.8	73.9
38AC	0.502	0.393	0.1979	0.1213	2.58	11,500	15,280	57,640	76,580	29.0	39.3	69.7
BC	0.504	0.440	0.1999	0.1520	2.51	11,810	15,490	59,100	77,400	25.5	23.8	70.3
CC	0.504	0.408	0.1995	0.1307	2.45	11,930	15,280	59,800	76,500	22.5	34.3	71.1
39AC	0.504	0.381	0.1995	0.1140	2.63	12,040	16,060	60,340	80,490	31.5	43.1	71.9
BC	0.502	0.411	0.1979	0.1326	2.52	12,310	16,000	62,200	80,800	26.0	33.0	72.7
CC	0.504	0.396	0.1995	0.1231	2.50	12,870	15,920	64,400	79,800	25.0	38.2	70.9

Table XII

Mechanical Properties of Forged Steels

Material No.	Av. Yield Point lb./in.^{2}	Av.Ult. Tens. Str. lb./in.^{2}	Av. Elong. % in 2"	Av. Red. of Area, %	Av. Hardness Rockwell 30T
20F	34,700	56,200	44.0	67.3	58.0
21F	40,500	57,500	41.3	70.3	60.8
22F	42,900	58,800	44.3	68.5	61.8
23F	42,700	58,400	41.2	68.9	61.2
24F	50,000	66,200	37.0	64.6	65.7
25F	49,100	61,600	41.3	68.5	63.6
26F	46,300	61,400	41.3	68.8	64.9
27F	53,200	65,200	41.0	67.0	68.0
28F	50,300	62,700	39.8	67.5	66.4
29F	53,800	63,400	40.3	67.7	65.9
30F	48,500	74,700	36.7	57.2	67.1
31F	51,900	77,700	33.7	55.8	69.3
32F	52,700	77,600	32.8	55.6	68.7
33F	53,300	78,300	33.2	55.1	69.7
34F	58,600	80,800	33.7	55.0	71.2
35F	57,900	79,300	34.2	57.8	72.1
36F	58,000	78,500	33.3	58.2	70.9
37F	64,900	83,200	31.2	56.2	72.9
38F	64,300	83,100	31.5	56.6	73.2
39F	63,000	79,300	31.5	55.3	71.4

Table XIII

Mechanical Properties of Cast Steels

Material No.	Av. Yield Point lb./in.^{2}	Av.Ult. Tens. Str. lb./in.^{2}	Av. Elong. % in 2"	Av. Red. of Area, %	Av. Hardness Rockwell 30T
20C	33,500	53,000	42.8	63.4	53.8
21C	35,700	56,900	38.3	59.5	59.6
22C	39,400	58,400	38.8	57.1	61.2
23C	40,000	58,600	38.8	57.1	61.4
24C	42,900	60,700	37.8	57.3	63.4
25C	44,600	60,600	37.8	57.9	64.5
26C	46,200	61,200	36.0	59.8	65.5
27C	49,800	63,900	37.7	53.9	67.3
28C	50,200	64,200	37.0	62.0	67.3
29C	52,000	63,900	36.0	55.6	66.0
30C	46,500	73,800	29.3	34.4	67.5
31C	54,300	77,700	27.7	32.8	70.2
32C	53,600	76,900	24.0	29.7	71.2
33C	50,200	71,600	26.0	29.3	67.7
34C	59,300	80,000	24.3	30.2	72.1
35C	56,700	78,100	24.0	24.6	72.7
36C	57,900	78,000	24.7	28.7	70.9
37C	63,400	82,900	23.8	29.7	73.8
38C	58,900	76,800	25.7	32.5	70.4
39C	62,300	80,400	27.5	38.1	71.8

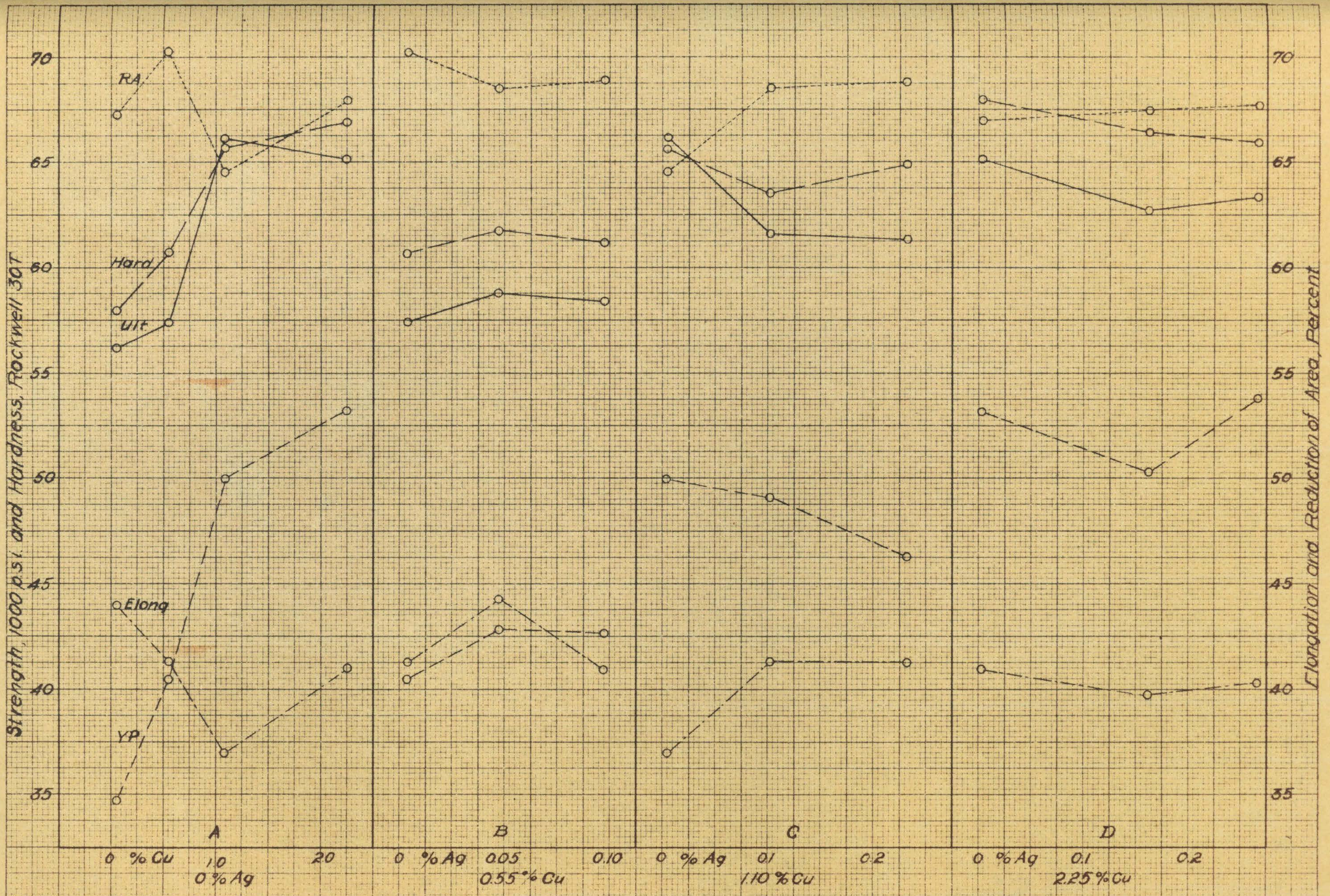


Figure 46-Mechanical Properties, 0.15 % C Forged Steels

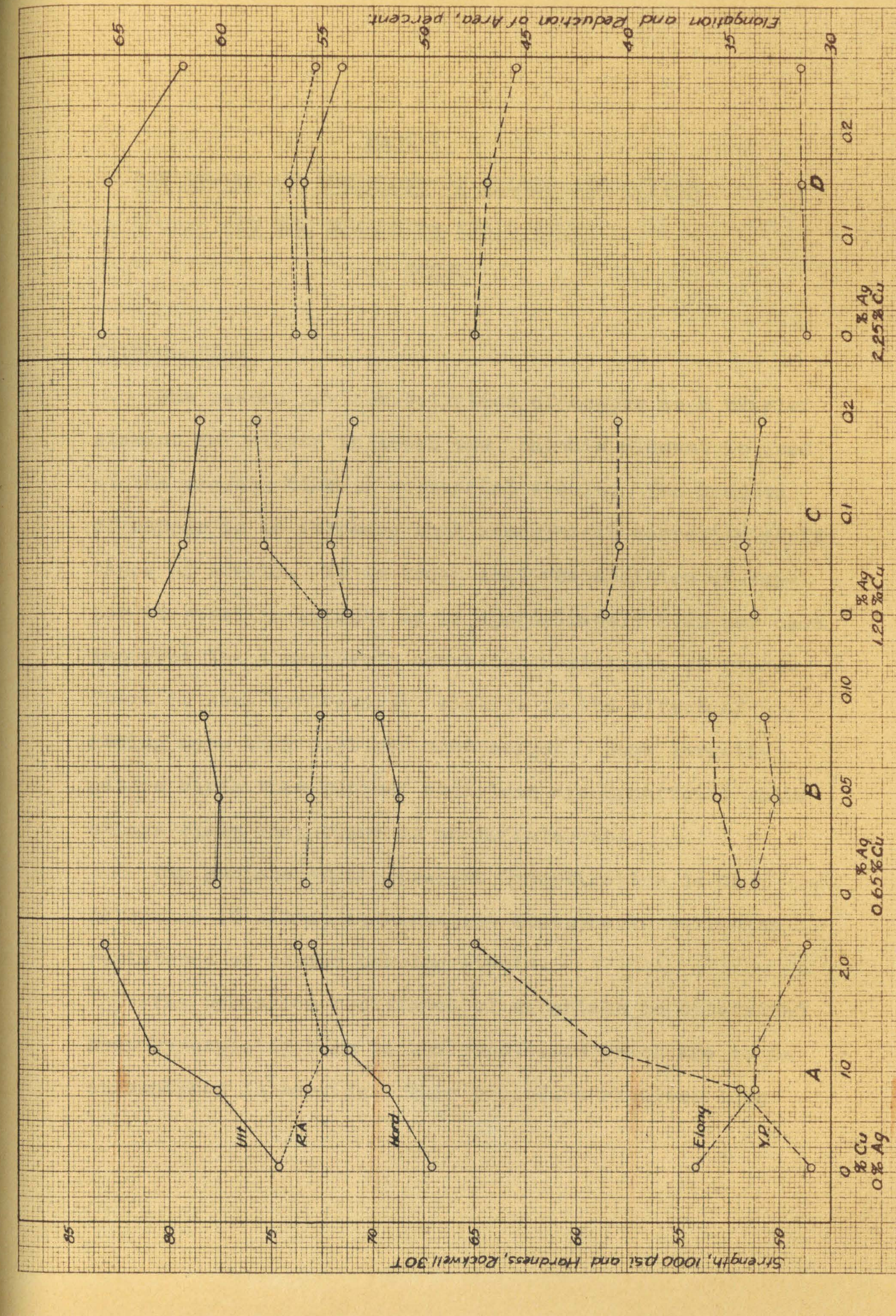


Figure 47 Mechanical Properties, 0.35 % C Forged Steels

PART V.

THE EFFECT OF ADDITIONS OF SILVER AND COPPER ON THE CORROSION RESISTANCE OF STEEL

Introduction

One reason for the selection of copper as a carrier element for silver in steel was that this element is used at the present time in commercial steels. The purpose of copper is to increase that atmospheric corrosion resistance of steels. It is known that the addition of copper to steel in amounts up to approximately 0.25 per cent improves the atmospheric corrosion resistance of steel. There is some controversy relative to the effect of adding more than 0.25 per cent copper. Some investigators claim that further additions are beneficial while others claim that there is no improvement.

The purpose of the present investigation is to determine if silver augments the atmospheric corrosion resistance of copper bearing steels.

The corrosion resistance of materials is determined best by exposing them to the conditions which are to be encountered in service. This procedure requires long periods of exposure to the corrosive conditions and therefore is not convenient for laboratory investigation. Numerous accelerated tests have been devised for corrosion testing. These tests are valuable for preliminary work, although they often produce erratic and misleading results. It is common practice in corrosion testing to subject samples of the material to an atmosphere supersaturated with water. This procedure was therefore adopted for the investigation.

Apparatus

For these tests a spray box was built in accordance with A.S.T.M. Tentative Standard B117-39T. Figures 48 and 49 are photographs of the spray box. The atmosphere to which the specimens are exposed is produced by atomizing tap water. Compressed air is passed through a cleaner and bubbled through a column of water before it reaches the atomizer (A). The tap water is drawn into the atomizer at a rate of approximately 400 cc. per hour, and blown out in a very fine mist. The specimens are mounted on glass rods and separated by pieces of glass tubing as shown at B. A glass plate is placed on the supports (C) above the atomizer to protect the specimens from direct spray and to distribute the mist. While the specimens

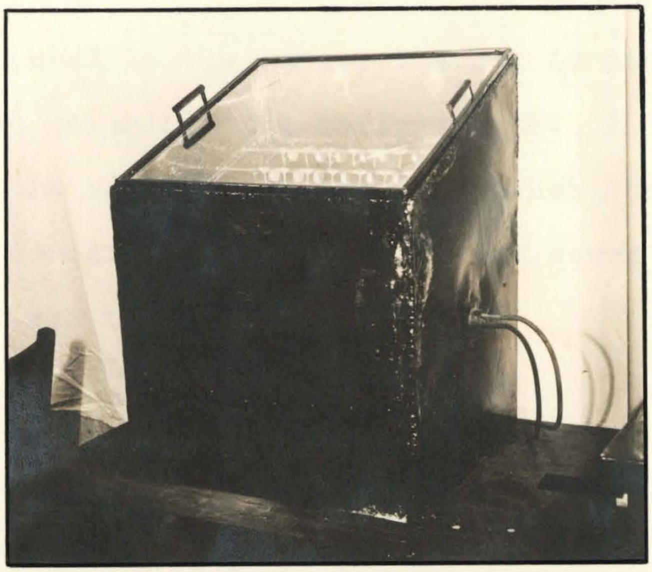


Figure 48.

Spray Box

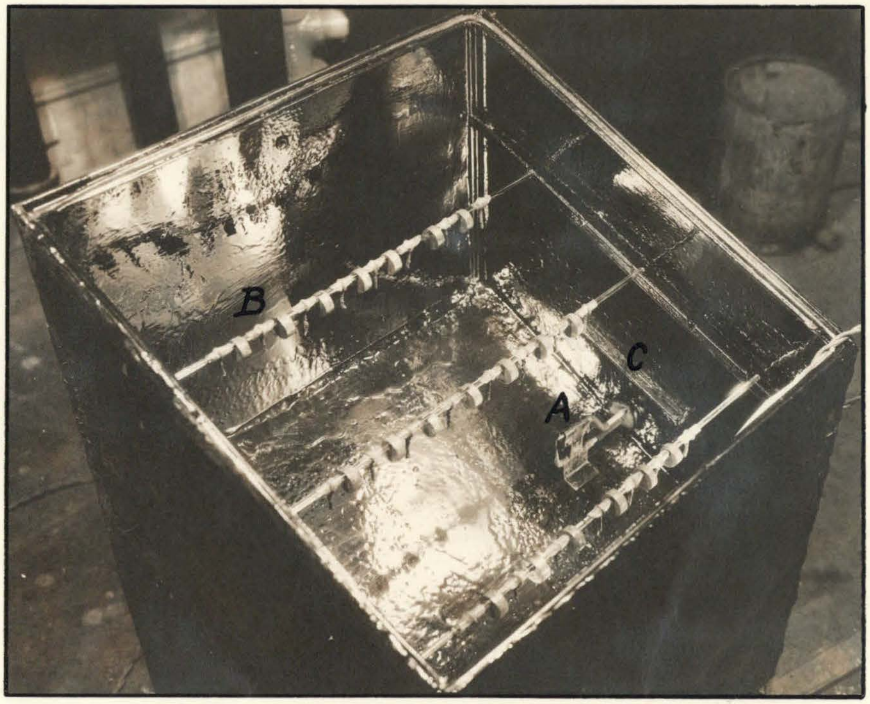


Figure 49.

Interior of Spray Box

are being exposed to the spray, the box is covered with a glass plate to maintain a uniform mist. A vent is provided in the back of the box to exhaust the air. The water which condenses is drained to the sewer through an outlet at the bottom.

Procedure

The specimens for these tests were taken from the forged steel bars. The analyses are given in Table VIII. They were ground and finished with #320 Aloxite paper and then washed in water and alcohol, dried, and degreased with trichlor-ethylene vapor. After degreasing they were weighed on a precision balance. Three separate tests were made: the first, for 24 hours, the second, for 49 hours, and the third, for 430 hours. The first test was made on one specimen of each of the forged bars. They were approximately 7/8 inch in diameter and 3/8 inch thick. A hole was drilled in each specimen for mounting. Figure 50 is a drawing of a specimen. The dimensions, surface

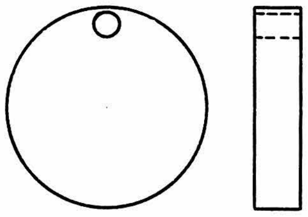


Figure 50

area, and weight of each specimen are given in Table XIV.

After exposing the specimens to the spray continuously for 24 hours they were scrubbed in gasoline and alcohol to remove the scale and then washed in alcohol, degreased in trichlor-ethylene vapor and weighed. The final weights and the loss in weight per unit area are recorded in Table XIV.

The results obtained from this test warrented no definite conclusion. Therefore, three specimens of each material were taken from the forged bars and polished. These specimens were smaller than the first, being approximately 13/16 inch in diameter and 5/16 inch thick. The actual dimensions and surface area are given in Table XV. The same procedure was followed in this test as in the first except that the specimens remained in the corrosion chamber 49 hours. All pertinent data are given in Table XVI.

When the specimens were weighed after removal from the corrosion chamber it was found that they had gained appreciable weight during the first hour after cleaning. This gain was due, possibly to the formation of a thin oxide film.

Table XIV Results of 24 Hour Test

Spec. No.	Diam., in.	Thickness, in.	Hole diam., in.	Surface Area, in.^{2}	Initial Weight, gms.	Weight after test, gms.	Loss in Weight	
							gms.	gms./in.^{2}
20A	0.881	0.379	0.25	2.498	27.9064	27.9012	0.0052	0.00208
21A	0.864	0.389	0.25	2.428	27.4482	27.4446	0.0036	0.00148
22A	0.882	0.353	0.25	2.375	25.8375	25.8339	0.0036	0.00152
23A	0.881	0.369	0.25	2.415	27.0918	27.0890	0.0028	0.00116
24A	0.880	0.375	0.25	2.441	27.3552	27.3522	0.0030	0.00123
25A	0.883	0.373	0.25	2.448	27.5708	27.5672	0.0036	0.00147
26A	0.877	0.359	0.25	2.376	26.2026	26.1994	0.0032	0.00135
27A	0.883	0.388	0.25	2.486	28.4526	28.4493	0.0033	0.00133
28A	*	0.378	0.25	—	28.1357	28.1320	0.0037	—
29A	*	0.383	0.25	—	25.8923	25.8937	-0.0014**	—
30A	*	0.381	0.25	—	27.5759	27.5684	0.0075	—
31A	*	0.364	0.25	—	25.5036	25.4981	0.0055	—
32A	0.875	0.373	0.25	2.415	27.1232	27.1201	0.0031	0.00129
33A	*	0.372	0.25	—	26.3204	26.3163	0.0041	—
34A	0.870	0.375	0.25	2.403	26.8824	26.8769	0.0054	0.00224
35A	0.878	0.386	0.25	2.475	28.1090	28.1045	0.0045	0.00182
36A	0.875	0.379	0.25	2.435	27.5299	27.5261	0.0038	0.00156
37A	0.876	0.376	0.25	2.431	27.2906	27.2866	0.0040	0.00164
38A	0.879	0.315	0.25	2.231	23.0725	23.0685	0.0040	0.00179
39A	0.872	0.374	0.25	2.405	26.9283	26.9239	0.0044	0.00183

* Irregular.

** Increase in weight due to formation of scale and retention of moisture in cracks in specimen.

Table XV Dimensions of Specimens

Specimen No.	Diameter in.	Thickness in.	Hole Diameter in.	Surface sq. in.
20B	0.811	0.270	0.25	1.834
20C	0.811	0.277	0.25	1.858
21B	0.811	0.307	0.25	1.953
21C	0.811	0.306	0.25	1.952
22B	0.810	0.296	0.25	1.913
22C	0.811	0.238	0.25	1.729
23B	0.812	0.308	0.25	1.963
23C	0.812	0.283	0.25	1.881
24B	0.812	0.272	0.25	1.844
24C	0.812	0.289	0.25	1.910
25B	0.813	0.286	0.25	1.893
25C	0.813	0.261	0.25	1.813
26B	0.811	0.282	0.25	1.872
26C	0.812	0.259	0.25	1.801
27B	0.801	0.251	0.25	1.738
27C	0.801	0.264	0.25	1.781
28B	0.811	0.277	0.25	1.845
28C	0.811	0.265	0.25	1.816
29B	0.809	0.281	0.25	1.862
29C	0.810	0.288	0.25	1.888
30B	0.809	0.283	0.25	1.868
30C	0.810	0.270	0.25	1.830
31B	0.807	0.283	0.25	1.862
31C	0.808	0.280	0.25	1.855
32B	0.811	0.279	0.25	1.863
32C	0.811	0.270	0.25	1.853
33B	0.810	0.281	0.25	1.866
33C	0.810	0.284	0.25	1.875
34B	0.809	0.281	0.25	1.862
34C	0.810	0.277	0.25	1.852
35B	0.811	0.225	0.25	1.686
35C	0.811	0.283	0.25	1.876
36B	0.809	0.282	0.25	1.867
36C	0.810	0.280	0.25	1.866
37B	0.811	0.275	0.25	1.850
37C	0.810	0.279	0.25	1.859
38B	0.810	0.271	0.25	1.834
38C	0.811	0.277	0.25	1.857
39B	0.810	0.277	0.25	1.854
39C	0.811	0.283	0.25	1.875

Table XVI Results of 49 Hour Test

Specimen No.	Surface Area sq. in.	Initial Weight gms.	Weight after Test gms.	Loss in Weight	
				gms.	gms./sq.in.
20A	2.498	27.3119	27.2925	0.0194	0.00777
B	1.834	16.2860	16.2708	0.0152	0.00830
C	1.858	16.7175	16.7062	0.0113	0.00609
21A	2.428	26.7684	26.7599	0.0085	0.00350
B	1.953	18.5151	18.5061	0.0090	0.00460
C	1.952	18.4314	18.4218	0.0096	0.00492
22A	2.375	25.4318	25.4215	0.0103	0.00434
B	1.913	17.8244	17.8130	0.0114	0.00596
C	1.729	14.3060	14.2977	0.0083	0.00480
23A	2.415	26.5624	26.5515	0.0109	0.00451
B	1.963	18.6302	18.6201	0.0101	0.00513
C	1.881	17.1336	17.1233	0.0103	0.00548
24A	2.441	26.9494	26.9394	0.0100	0.00410
B	1.844	16.4523	16.4428	0.0095	0.00515
C	1.910	17.5140	17.5034	0.0106	0.00555
25A	2.448	27.0275	27.0158	0.0117	0.00478
B	1.893	17.0948	17.0844	0.0104	0.00550
C	1.813	15.5827	15.5740	0.0087	0.00480
26A	2.376	25.6302	25.6183	0.0119	0.00500
B	1.872	17.0047	16.9979	0.0068	0.00363
C	1.801	15.6196	15.6123	0.0073	0.00404
27A	2.486	27.9537	27.9442	0.0095	0.00383
B	1.738	14.6038	14.5954	0.0084	0.00484
C	1.781	15.5366	15.5291	0.0075	0.00420
28A	*	27.0374	27.0298	0.0076	—
B	1.845	16.6842	16.6765	0.0077	0.00417
C	1.816	16.0981	16.0895	0.0086	0.00473
29A	*	—	—	—	—
B	1.862	16.9098	16.9028	0.0070	0.00375
C	1.888	17.3410	17.3323	0.0087	0.00461

* Irregular.

(Table IV continued on page 117)

Table XVI Results of 49 Hour Test. (continued from page 116)

Specimen No.	Surface Area sq. in.	Initial Weight gms.	Weight after Test gms.	Loss in Weight	
				gms.	gms./sq.in.
30A	*	26.5879	26.5619	0.0260	---
B	1.868	16.7670	16.7515	0.0155	0.00830
C	1.830	16.2245	16.2107	0.0138	0.00753
31A	*	23.0748	23.0628	0.0120	---
B	1.862	16.8774	16.8681	0.0093	0.00499
C	1.855	16.7175	16.7077	0.0098	0.00528
32A	2.415	26.4933	26.4844	0.0089	0.00368
B	1.863	16.8504	16.8377	0.0127	0.00681
C	1.853	16.3587	16.3475	0.0112	0.00604
33A	*	25.3687	25.3527	0.0160	---
B	1.866	16.8815	16.8709	0.0106	0.00567
C	1.875	17.0783	17.0651	0.0132	0.00704
34A	2.403	26.2959	26.2806	0.0153	0.00637
B	1.862	16.8579	16.8468	0.0111	0.00596
C	1.852	16.7880	16.7798	0.0082	0.00433
35A	2.475	27.7157	27.7029	0.0128	0.00477
B	1.686	13.5035	13.4957	0.0078	0.00467
C	1.876	17.0852	17.0769	0.0083	0.00435
36A	2.435	26.9491	26.9406	0.0085	0.00350
B	1.867	16.9840	16.9750	0.0090	0.00482
C	1.866	16.8733	16.8666	0.0067	0.00358
37A	2.431	26.7236	26.7143	0.0093	0.00383
B	1.850	16.5241	16.5154	0.0087	0.00470
C	1.859	16.8155	16.8085	0.0070	0.00376
38A	2.231	22.5822	22.5701	0.0121	0.00542
B	1.834	16.3107	16.3026	0.0081	0.00442
C	1.857	16.6600	16.6508	0.0092	0.00495
39A	2.405	26.4487	26.4395	0.0092	0.00382
B	1.854	16.7387	16.7313	0.0074	0.00399
C	1.875	17.0828	17.0733	0.0095	0.00507

* Irregular.

To check this condition, three samples were cleaned in the normal manner and weighed at intervals. The results are given in Table XVII. From this table it is apparent that the specimens gained approximately 0.004 per cent in weight while standing in air for the first five hours and after that there was no appreciable gain. In view of this condition, a third test was made.

The specimens used in the previous test were repolished and cleaned as before, placed in air for more than 5 hours and weighed. They were then placed in the corrosion chamber. After 430 hours the specimens were removed from the chamber and de-scaled by scrubbing in alcohol and dipping in a very dilute hydrochloric acid solution. They were then cleaned in alcohol, degreased, and placed in air for more than 5 hours, and then weighed. All the data for this test are found in Table XVIII. The corrosion was computed on the basis of loss of weight per unit area.

Results

The type of corrosion and the nature of the scale was essentially the same for all of the specimens. The corrosion consisted of two types of attacks. Pitting

Table XVII Gain in Weight of Specimen after Cleaning

Specimen No.	Weight, gms.	Time after Cleaning hours:min.	Change in Weight gms.
20A	26.7920	0:0	—
	26.7927	0:44	+0.0007
	26.7929	3:10	+0.0009
	26.7929	5:28	+0.0009
	26.7929	21:00	+0.0009
	26.7929	26:15	+0.0009
21B	18.0497	0:0	—
	18.0504	0:42	+0.0007
	18.0505	3:08	+0.0008
	18.0506	5:28	+0.0009
	18.0506	20:57	+0.0009
	18.0506	26.13	+0.0009
31A	22.4647	0:0	—
	22.4652	0:42	+0.0005
	22.4653	3:06	+0.0006
	22.4654	5:25	+0.0007
	22.4654	20:55	+0.0007
	22.4654	26:12	+0.0007

Table XVIII Results of 430 Hour Test

Specimen No.	Surface Area sq. in.	Initial Weight gms.	Weight after Test gms.	Loss in Weight gms.	Loss in Weight gms./sq.in.
20A	2.498	26.7929	26.6534	0.1395	0.0558
B	1.834	15.7797	15.6802	0.0995	0.0542
C	1.858	16.1898	16.1094	0.0804	0.0433
21A	2.428	26.2422	26.1733	0.0689	0.0284
B	1.953	18.0506	17.9985	0.0521	0.0267
C	1.952	17.9333	17.8812	0.0521	0.0267
22A	2.375	24.8649	24.7964	0.0685	0.0288
B	1.913	17.3569	17.2930	0.0639	0.0334
C	1.729	13.8734	13.8159	0.0575	0.0333
23A	2.415	25.9188	25.8449	0.0739	0.0306
B	1.963	18.0168	17.9679	0.0489	0.0249
C	1.881	16.6899	16.6284	0.0615	0.0327
24A	2.441	26.3849	26.3061	0.0788	0.0323
B	1.844	15.9441	15.8837	0.0604	0.0328
C	1.910	16.9541	16.8941	0.0600	0.0314
25A	2.448	26.3688	26.2759	0.0929	0.0379
B	1.893	16.6666	16.6083	0.0583	0.0307
C	1.813	15.1010	15.0304	0.0706	0.0389
26A	2.376	25.0633	24.9698	0.0935	0.0394
B	1.872	16.5344	16.4801	0.0543	0.0290
C	1.801	15.2527	15.1884	0.0643	0.0357
27A	2.486	27.4121	27.3354	0.0767	0.0308
B	1.738	14.2016	14.1658	0.0358	0.0206
C	1.781	15.1066	15.0475	0.0591	0.0332
28A	*	26.3521	26.2573	0.0948	—
B	1.845	16.2039	16.1329	0.0710	0.0385
C	1.816	15.6211	15.5577	0.0634	0.0349
29A	*	—	—	—	—
B	1.862	16.3571	16.3004	0.0567	0.0304
C	1.888	16.8650	16.8127	0.0523	0.0277

* Irregular

(Table 18 continued on page 121)

Table XVIII Results of 430 Hour Test (continued from page 120)

Specimen No.	Surface Area sq. in.	Initial Weight gms.	Weight after Test gms.	Loss in Weight	
				gms.	gms./sq.in.
30A	*	25.8585	25.7388	0.1198	--
B	1.868	16.2275	16.1322	0.0953	0.0510
C	1.830	15.7525	15.6685	0.0840	0.0459
31A	*	22.4657	22.3850	0.0807	--
B	1.862	16.3657	16.2831	0.0826	0.0443
C	1.855	16.2508	16.1628	0.0880	0.0475
32A	2.415	25.8136	25.7353	0.0783	0.0324
B	1.863	16.2895	16.2242	0.0653	0.0350
C	1.853	15.9316	15.8781	0.0535	0.0289
33A	*	24.5454	24.4439	0.1015	--
B	1.866	16.3784	16.3253	0.0531	0.0284
C	1.875	16.5980	16.5471	0.0509	0.0272
34A	2.403	25.6805	25.6003	0.0802	0.0333
B	1.862	16.3534	16.2947	0.0587	0.0315
C	1.852	16.2758	16.2303	0.0455	0.0244
35A	2.475	27.0585	26.9890	0.0695	0.0281
B	1.686	13.0822	13.0172	0.0650	0.0386
C	1.876	16.5360	16.4834	0.0526	0.0280
36A	2.435	26.3166	26.2307	0.0859	0.0353
B	1.867	16.5326	16.4731	0.0595	0.0319
C	1.866	16.4586	16.3950	0.0636	0.0341
37A	2.431	26.2034	26.1179	0.0855	0.0352
B	1.850	15.8437	15.7604	0.0833	0.0450
C	1.859	16.3938	16.3142	0.0796	0.0428
38A	2.231	21.9982	21.9411	0.0571	0.0256
B	1.834	15.8354	15.7866	0.0488	0.0256
C	1.857	16.1955	16.1445	0.0510	0.0274
39A	2.405	25.7573	25.6985	0.0588	0.0244
B	1.854	16.2212	16.1698	0.0514	0.0277
C	1.875	16.6106	16.5504	0.0602	0.0321

* Irregular

was observed rather uniformly over all the specimens. A much heavier attack was noted where small drops of water had collected on the specimen. The difference between the extent of the corrosion of the different specimens was largely in the amount of pitting and general attack. All of the samples were partly covered with a very porous scale which was washed off by the condensing moisture. Beneath the porous scale, there was a thin, tough, adherent film which could only be removed with dilute hydrochloric acid.

The quantitative results obtained in these tests are plotted in Figures 51 and 52. The range of the loss in weight per unit area is given for all tests. From the curves several conclusions are apparent. Copper definitely increases the corrosion resistance of SAE 1020 and 1040 steels by about 1/3. The greatest increase in corrosion resistance produced with less than 1 per cent copper. Additional amounts contribute very little. These two observations check very well with those of other investigators, thus indicating the general reliability of the present test. The results show that the effect of silver on the corrosion resistance of the copper steels is very slight. From these results it is not possible to state whether silver has a beneficial or detrimental effect. Whatever the effect may be, it is insignificant.

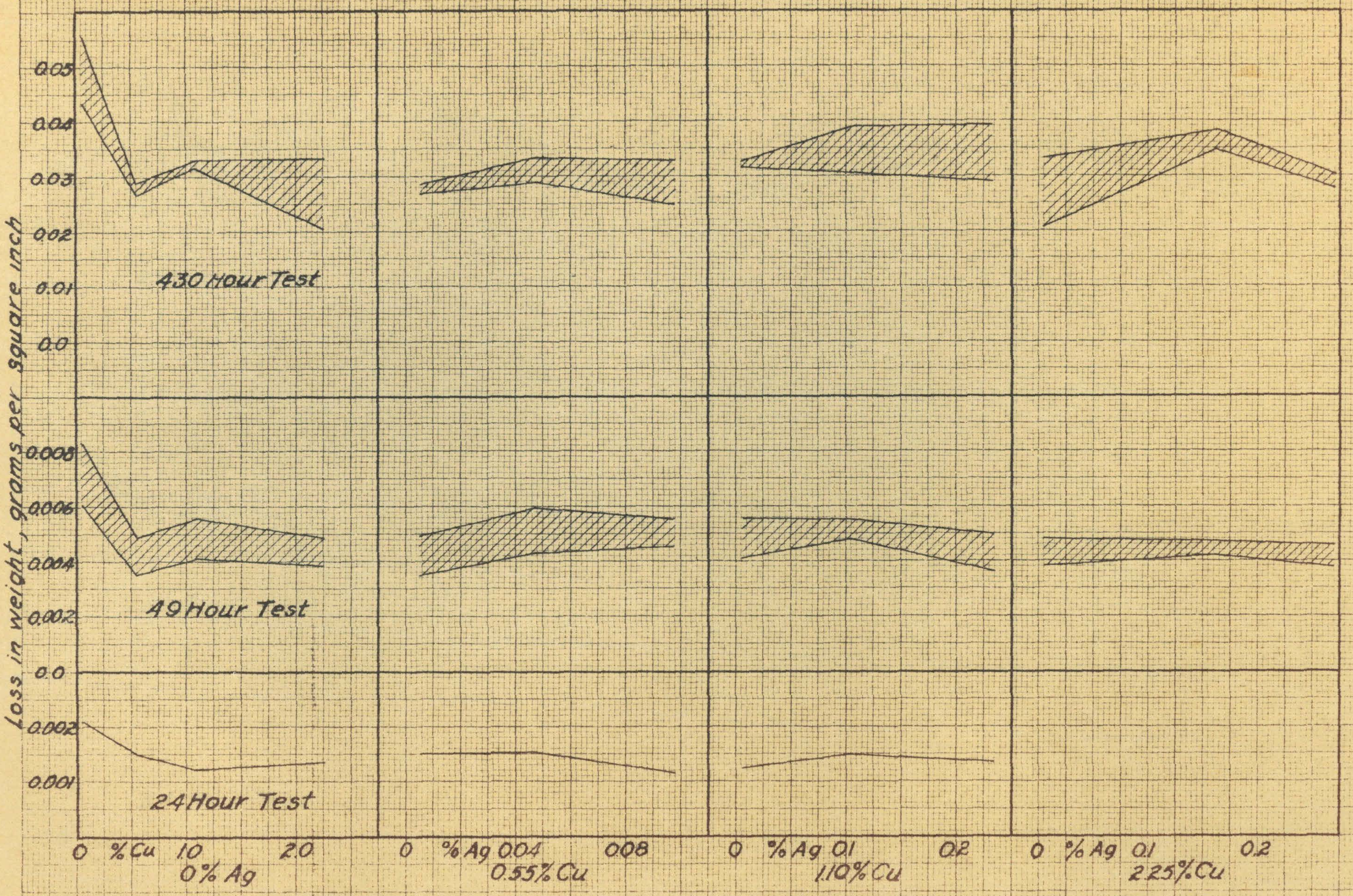


Figure 51—Corrosion Resistance, 0.15% C Forged Steels

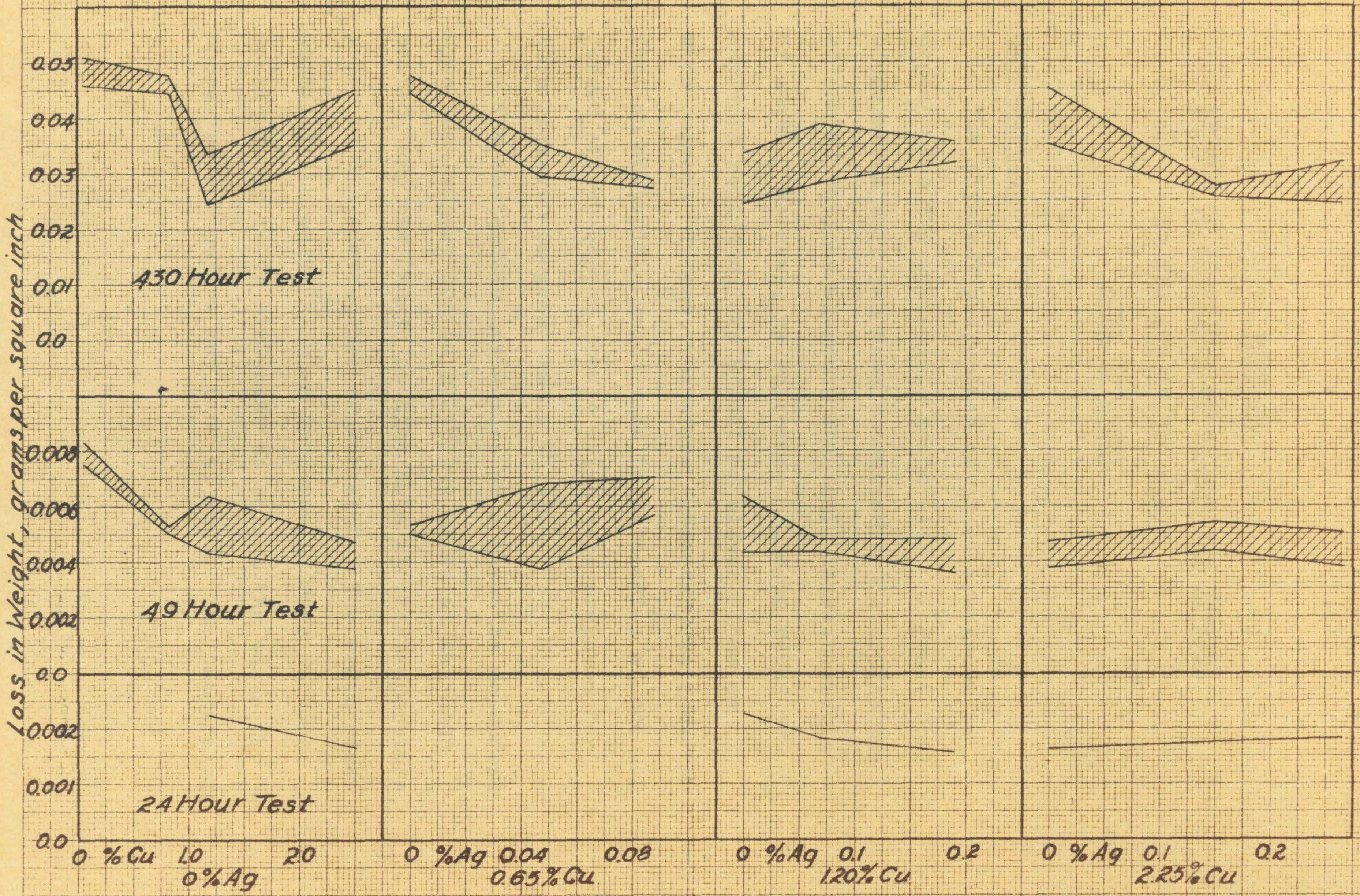


Figure 52—Corrosion Resistance, 0.35% C Forged Steels

PART VI.

EFFECT OF ADDITIONS OF SILVER AND COPPER ON THE AUSTENITIC GRAIN SIZE OF STEEL

Introduction

The physical properties of steel are known to depend upon the austenitic grain size. A great deal of research work has been conducted to determine the effect of various elements upon this characteristic of steel. However, no reference could be found of any work regarding the effect of silver alone or with copper. It was, therefore, necessary to conduct an austenitic grain size investigation of the forged silver-copper steels which were prepared for this research program (Table VIII).

The austenitic grain size of a steel is dependent upon the temperature to which the material has been heated, and the length of time held at that temperature, prior to the microscopic examination. The grain size normally increases with an increase in both factors. Consequently it is necessary to select the value for these factors before any test is made. The temperature must be above the Ac_3 temperature of the steel in question and the time must be sufficient to allow equilibrium to be established.

Methods of Determining Austenitic Grain Size

Four methods have been devised for the determination of the austenitic grain size of steels. Three of these are dependent upon the control of the rate of cooling through the transformation range, so that the bounderies of the austenite grains will be revealed. These four methods can be summarized as follows:

1. By the rejection of excess ferrite or cementite in the grain boundaries, a network is formed around the initial austenite grains.[13]
2. By interrupting the austenite transformation which begins predominantly at the grain boundaries, the grains are outlined.[13]
3. By etching the tempered martensite formed by quenching and tempering, the different orientations of the parent austenitic grains are revealed.
4. By high temperature etching, the grain boundaries are made visible.[14]

The first method indicated is applicable only to hypoeutectoid and hypereutectoid steels which have an excess of ferrite or cementite.

The second and third methods depend upon the formation of martensite, and so are limited to steels which have sufficient carbon to produce this structure.

The fourth method relies on the evaporation of the metal at elevated temperatures. It has been found that the grain boundary material vaporizes more rapidly than do the grains themselves and consequently, the grain size is revealed. In order to obtain sufficient delineation of the grain boundaries, it is necessary to resort to high temperatures. However, objectionable grain growth occurs with prolonged exposures to high temperatures; those greatly in excess of the critical temperatures. This method is consequently limited in its application to steels having high Ac_3 points, that is, low carbon steels.

Procedure

Since the two steels studied were of somewhat different carbon content, it was found necessary to use two of the above methods for determining the austenitic grain size. The 0.35 per cent carbon steels required the third method and the 0.15 per cent carbon steels, the fourth method. The 0.35 per cent carbon steels were heated to 1450 degrees F., which is 50 to 75 degrees

F. above the Ac_3 temperature. They were held at this temperature for 15 minutes and quenched in water. The specimens were then tempered in a salt bath at 600 degrees F. for 30 minutes and quenched in water. Following this treatment, the specimens were polished electrolytically in a solution of 172 cc of perchloric acid, 765 cc of acetic anhydride, and 63 cc of water. They were etched with a solution of 1 gram of picric acid and 5 cc of concentrated hydrochloric acid in 95 cc of ethyl alcohol. Photomicrographs were then taken of the structure at a magnification of 200 diameters and the grain size determination made. The photomicrographs are shown in Figures 53 to 62.

The 0.15 per cent carbon steels were heat etched to reveal the austenitic grain size. The specimens, after being polished, were heated in a purified hydrogen atmosphere within a fused silica tube. Tank hydrogen was first passed through a pyrogallic acid solution to remove the oxygen and finally through concentrated sulfuric acid and phosphorus pentoxide to remove all water vapor. The purified hydrogen passed over the specimens which were held at 1550 degrees F. The hydrogen, leaving the silica tube, was passed through two mercury traps and thence exhausted to the atmosphere. The temperature of the specimens was measured by means of an iron-constantan thermocouple. The specimens were held at temperature for $2\frac{1}{2}$ hours and then cooled in the furnace to 600 degrees F. They were removed and quenched in water.

When taken from the furnace, the specimens had a slight oxide coating, indicating that oxygen had not been completely removed from the hydrogen. However, the coating was not sufficient to obscure the structure. Photomicrographs were taken of the surface of each of the specimens at a magnification of 500 diameters and the grain size determined. The photomicrographs are shown in Figures 63 to 72.

Results

An examination of the photomicrographs reveal little, if any variation in the austenitic grain size of either the 0.35 per cent carbon or the 0.15 per cent carbon steels, with addition of silver and copper. All of the samples in each series were heated at one temperature; and the thermal critical temperatures varied over a range of 30 degrees F. Since grain growth is a function of temperature in excess of the Ac_3 temperature, the slight variation in grain size may be attributed to this difference in excess of temperature.

The specimens which did not contain any copper or silver had an exceedingly fine grain structure (ASTM designation 10). It is known that the austenitic grain size may be refined only to a certain point. Therefore, it is impossible to determine whether or not silver and copper have a refining effect upon the austenitic grains. It can be stated, however, that these two alloying elements do not coarsen the austenite grains of 0.15 per cent and 0.35 per cent carbon, aluminum-killed steels.

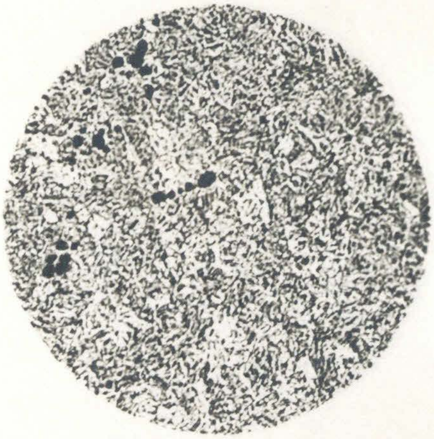


Figure 53.
Specimen 30
Magnification 200x

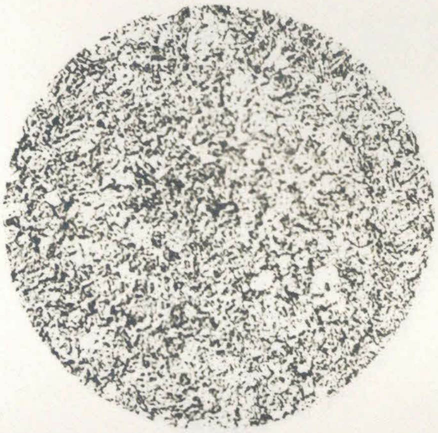


Figure 54.
Specimen 31
Magnification 200x

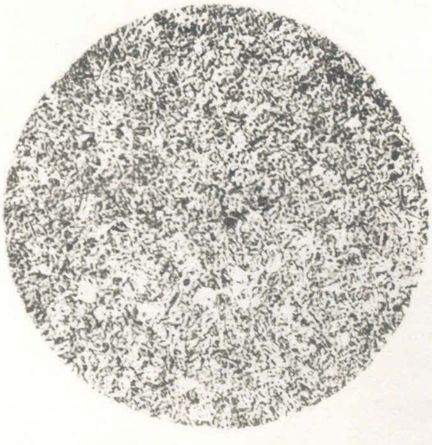


Figure 55.
Specimen 32
Magnification 200x

Figure 56.
Specimen 33
Magnification 200x

Austenitic Grain Size

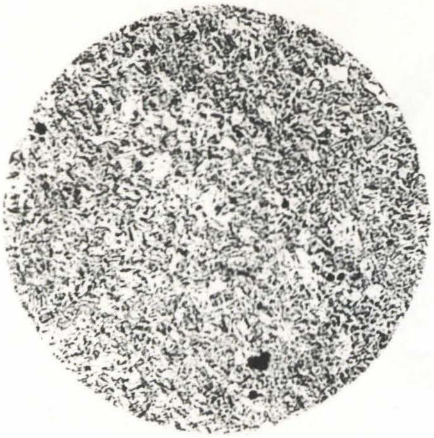


Figure 57.
Specimen 34
Magnification 200x

Figure 58.
Specimen 35
Magnification 200x

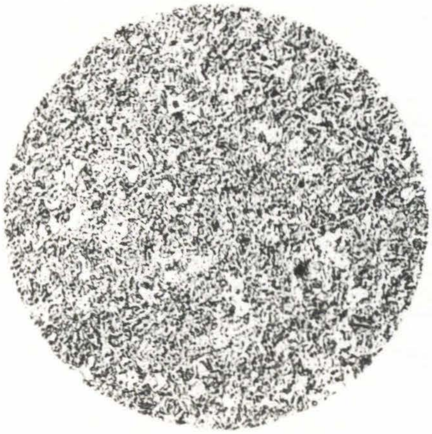


Figure 59.
Specimen 36
Magnification 200x

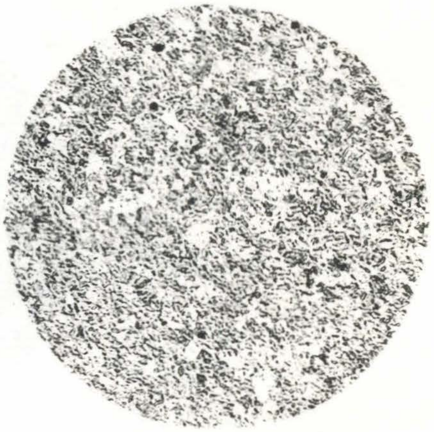


Figure 60
Specimen 37
Magnification 200x

Austenitic Grain Size

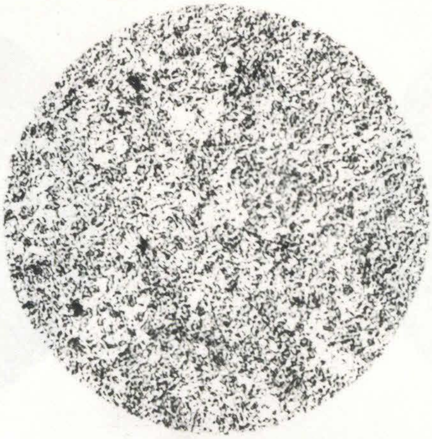


Figure 61.
Specimen 38
Magnification 200x

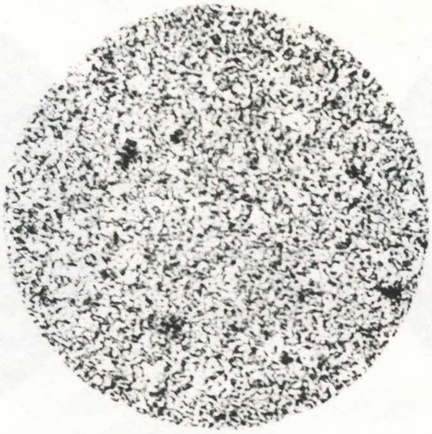


Figure 61.
Specimen 39
Magnification 200x

Austenitic Grain Size

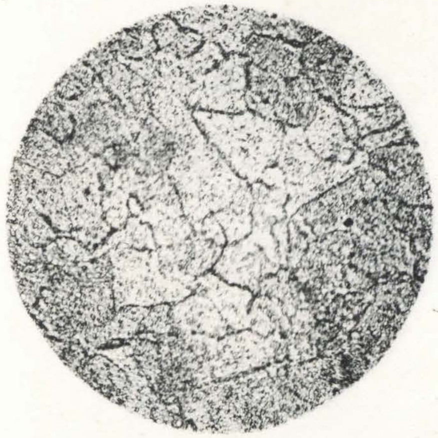


Figure 63.
Specimen 20
Magnification 500x

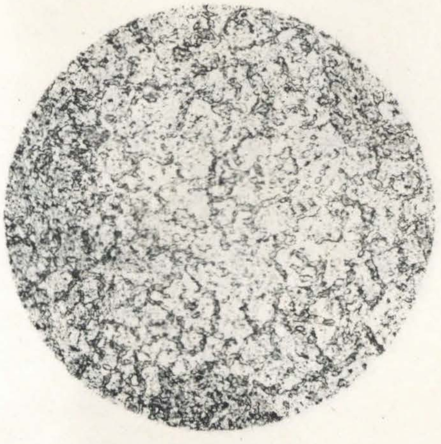


Figure 64.
Specimen 21
Magnification 500x

Figure 65.
Specimen 22
Magnification 500x

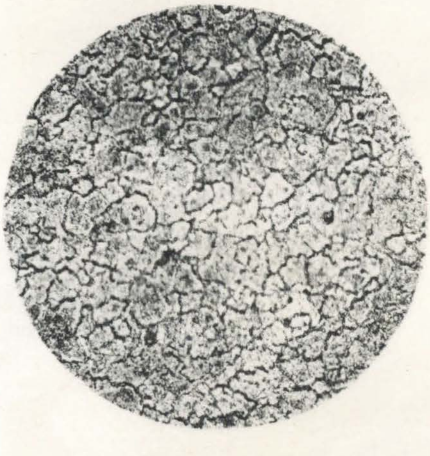


Figure 66.
Specimen 23
Magnification 500x

Austenitic Grain Size

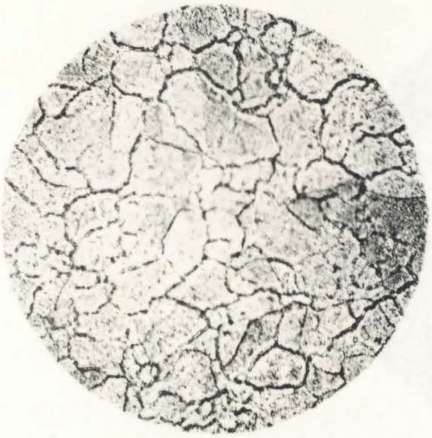


Figure 67.
Specimen 24
Magnification 500x

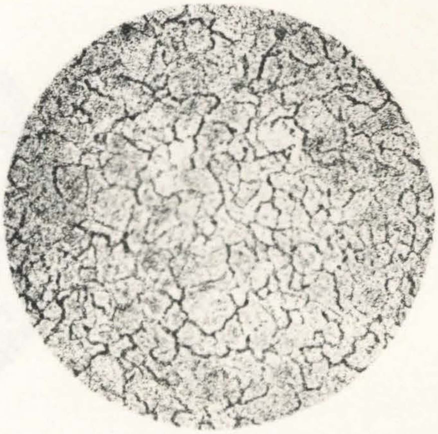


Figure 68.
Specimen 25
Magnification 500x

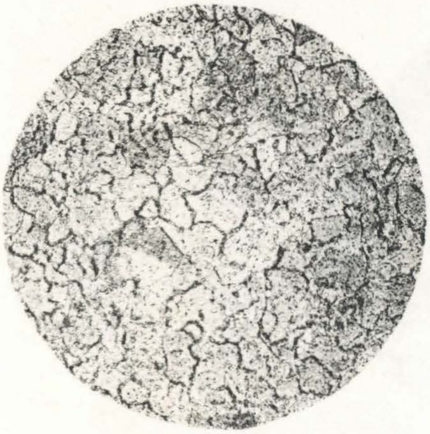


Figure 69.
Specimen 26
Magnification 500x

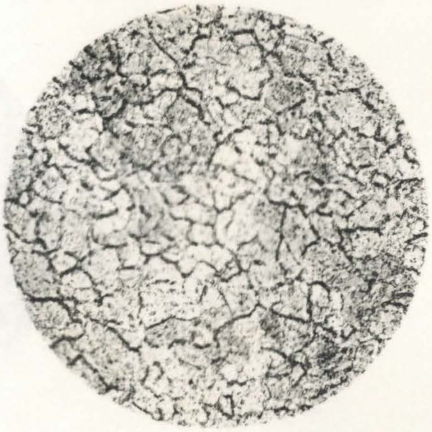


Figure 70.
Specimen 27
Magnification 500x

Austenitic Grain Size

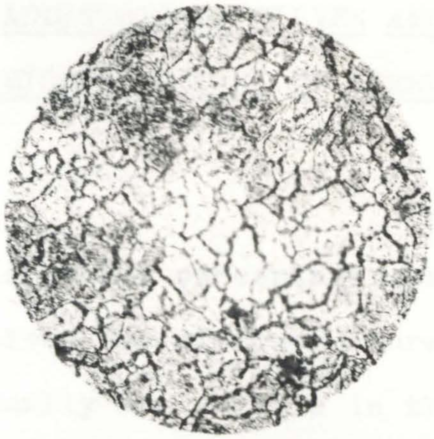


Figure 71.
Specimen 28
Magnification 500x

Figure 72.
Specimen 29
Magnification 500x

Austenitic Grain Size

PART VII.

THE EFFECT OF ADDITIONS OF SILVER AND COPPER ON THE MICROSTRUCTURE OF STEEL

Introduction

The additions of low percentages of alloying elements soldom alter the microstructure of steel. These elements usually are soluble in the ferrite or form intermetallic compounds with the iron and carbon. In either case, the structure is very similar to that of the plain carbon steels. The addition of copper, however, does slightly change the structure. If the percentage is very low, there is no change. With increasing copper content, the ferrite grains show evidence of staining when etched and a third phase becomes evident in the slowly cooled alloys. This third phase is a copper-rich solid solution which is precipitated on slow cooling. The reason for this precipitation is the decreasing solubility of copper in ferrite as the temperature is lowered (Figure 5). No reference could be found to the effect of additions of silver with copper on the microstructure of steel. Since the study of the microstructure is important in the understanding of the nature of alloys, it was decided to conduct an investigation of this character.

Procedure

Samples were removed from one end of the tensile test specimens of both the 0.15 per cent and 0.35 per cent carbon forged steels. The cast specimens were not examined, because of the great amount of segregation (Table IX). The samples were polished electrolytically in a solution of 172 cc of perchloric acid, 765 cc of acetic anhydride and 63 cc of water. They were then etched in 1 per cent Nital, and examined under the microscope. Photomicrographs were taken of each of the specimens at a magnification of 100 diameters and 500 diameters.

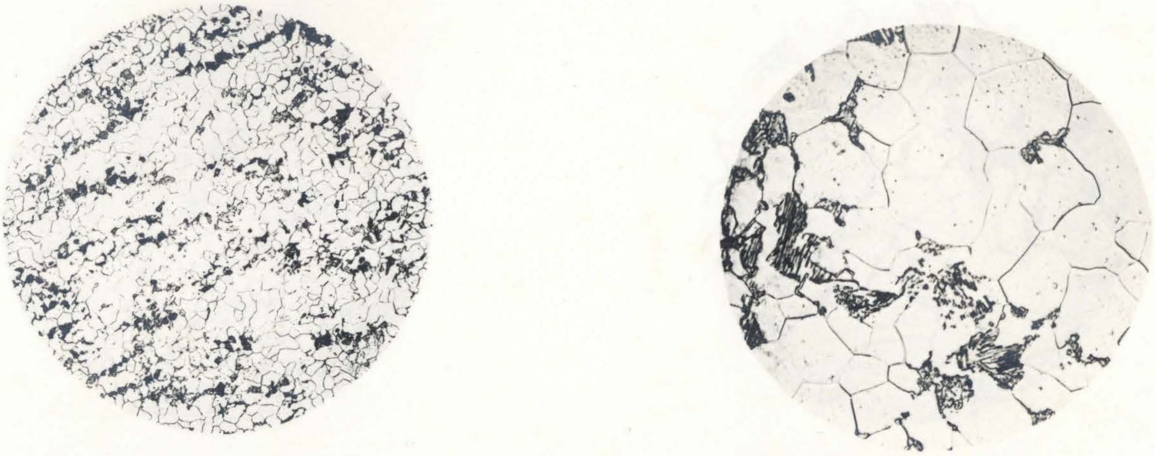
Results

The photomicrographs of this investigation are found in Figures 73 to 92. A study of these photomicrographs reveals that the additions of silver to the copper-bearing steels cause little change in the structure.

The photomicrographs at 500 diameters show some variation. As the copper content increases, a staining of the ferrite grains becomes evident. Also, small black specks appear in the ferrite grains. This is normal for the slow cooled copper bearing steels. The fine black particles are probably a copper-rich solid solution which has been precipitated from the ferrite. The addition of silver to the copper-bearing steels does not cause any alteration in the structure.

An attempt was made to detect the presence of free silver in the structure of these steels. Magnifications of as high as 2000 diameters did not reveal any silver. Several etching reagents were employed, but all of them attacked the iron or copper. It was therefore, impossivle to reach a definite conclusion as to the presence or absence of free silver. If silver is present in precipitated form it is so in extremely fine dispersion.

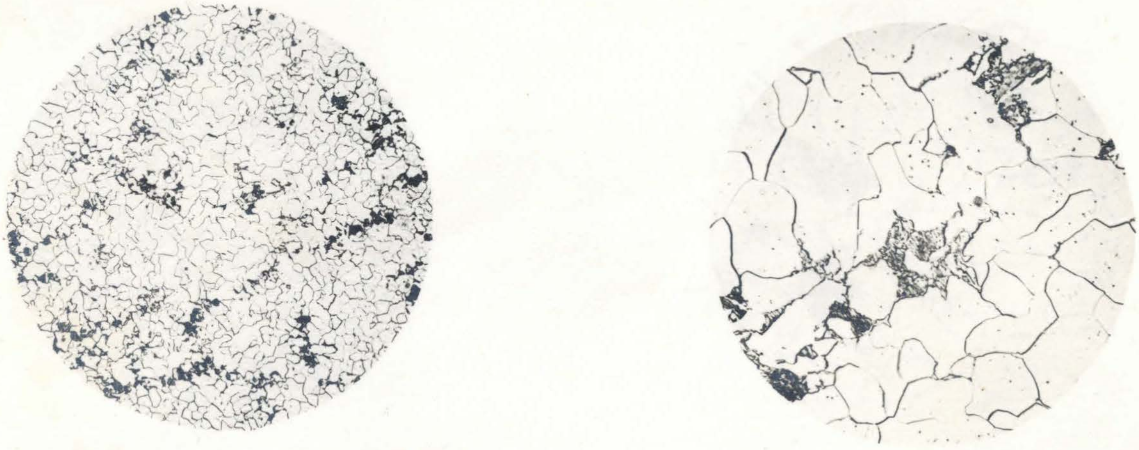
The photomicrographs at 100 diameters indicate that the steels retained the banded structure after the heat treatment. The pearlite, segregated during casting, flowed in the direction of forging. This is very evident in the steels containing 0.35 per cent carbon because of the larger amount of pearlite. However, there is no evidence here, of any change in the structure of steel with additions of silver with copper.



Magnification 100x

Magnification 500x

Figure 73.
Specimen 20

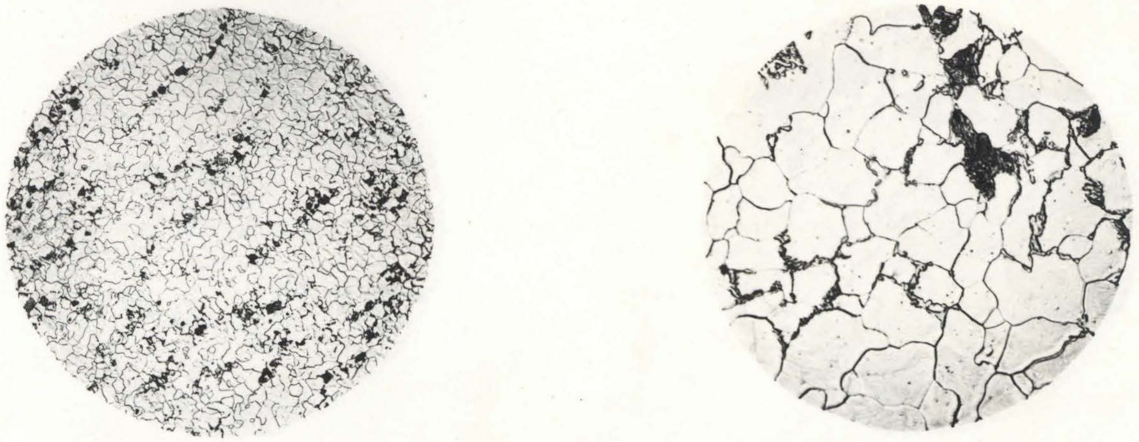


Magnification 100x

Magnification 500x

Figure 74.
Specimen 21

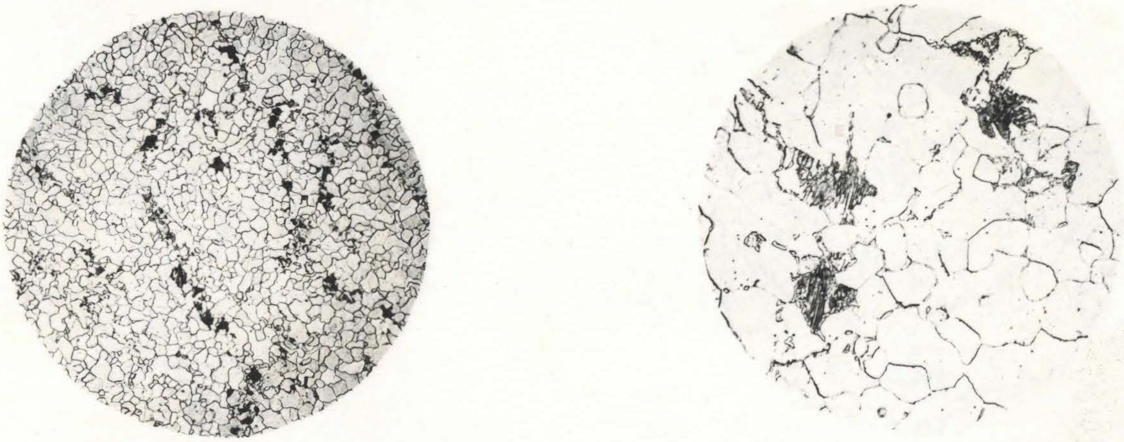
Microstructure of Forged and Annealed
Silver-Copper Steels



Magnification 100x

Magnification 500x

Figure 75.
Specimen 22



Magnification 100x

Magnification 500x

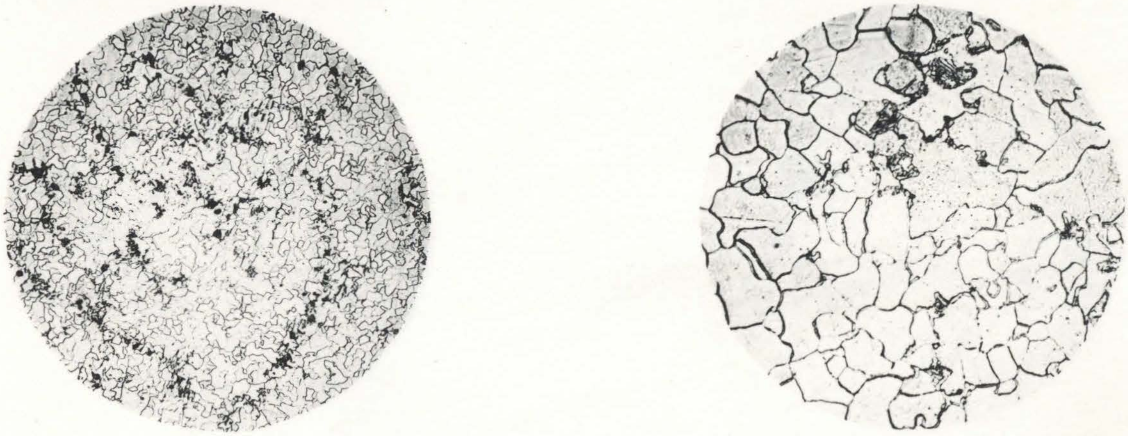
Figure 76.
Specimen 23

Microstructure of Forged and Annealed
Silver-Copper Steels

Magnification 100x

Magnification 500x

Figure 77.
Specimen 24

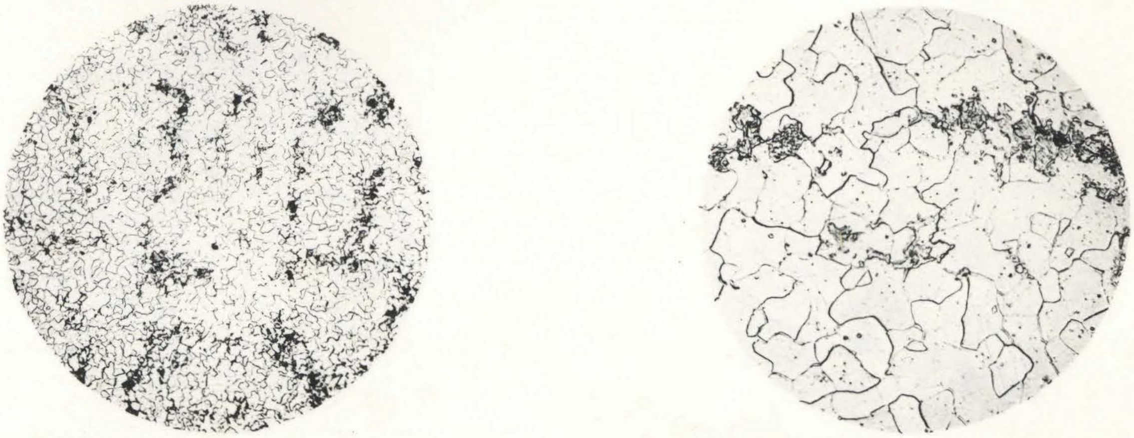


Magnification 100x

Magnification 500x

Figure 78.
Specimen 25

Microstructure of Forged and Annealed
Silver-Copper Steels



Magnification 100x

Magnification 500x

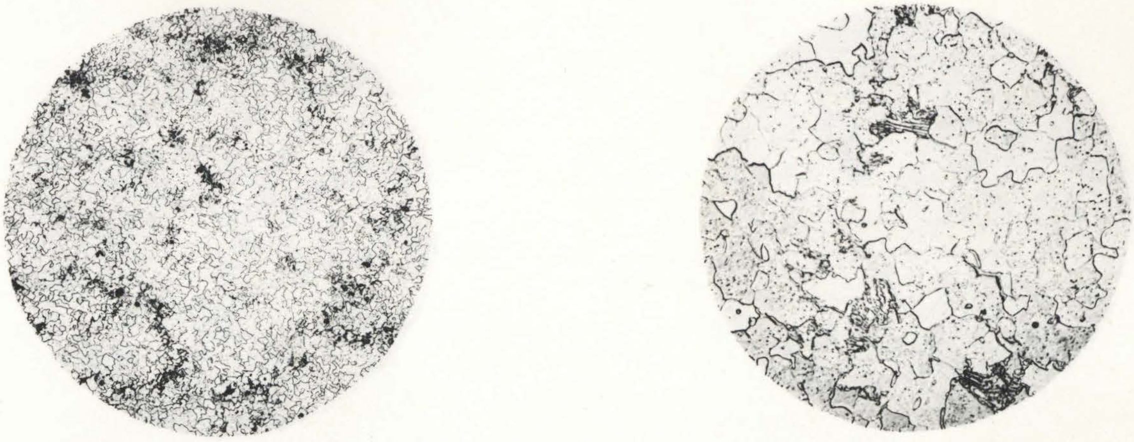
Figure 79.
Specimen 26

Magnification 100x

Magnification 500x

Figure 80.
Specimen 27

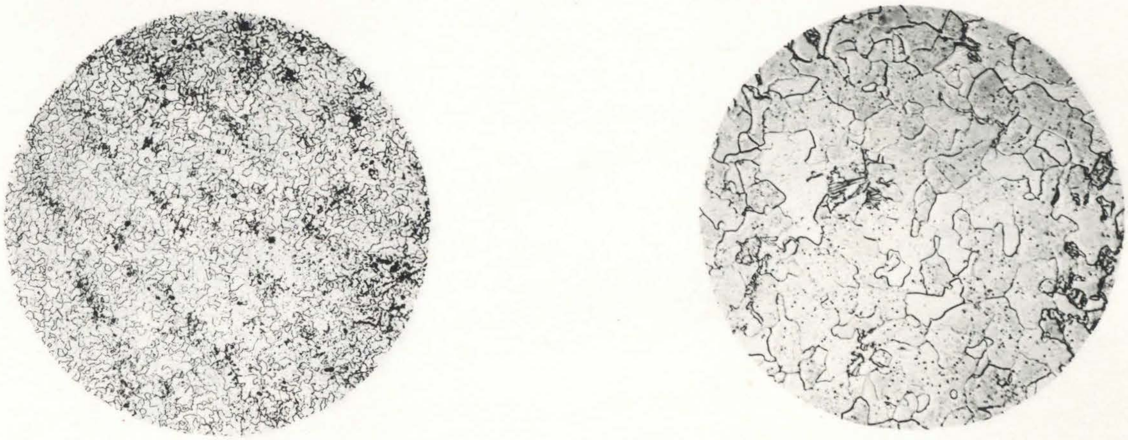
Microstructure of Forged and Annealed
Silver-Copper Steels



Magnification 100x

Magnification 500x

Figure 81.
Specimen 28



Magnification 100x

Magnification 500x

Figure 82.
Specimen 29

Microstructure of Forged and Annealed
Silver-copper Steels

Magnification 100x

Magnification 500x

Figure 83.
Specimen 30

Magnification 100x

Magnification 500x

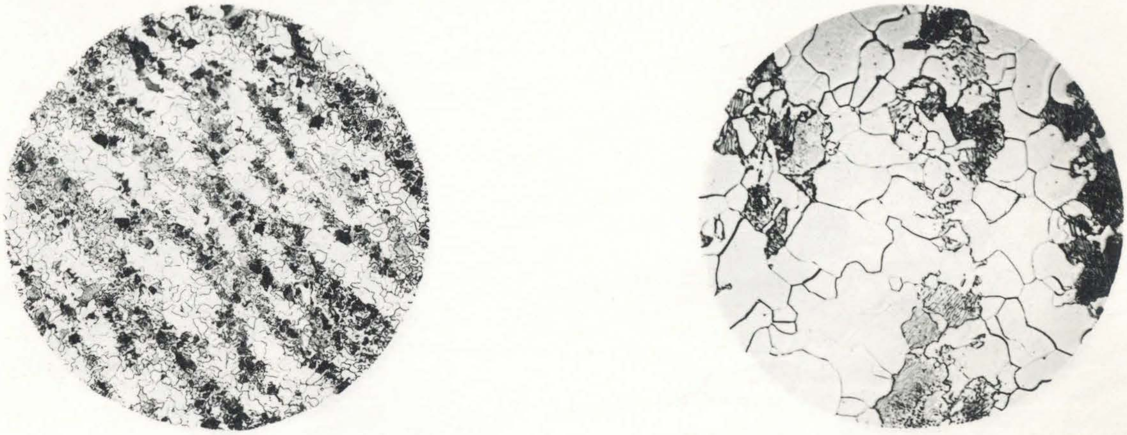
Figure 84.
Specimen 31

Microstructure of Forged and Annealed
Silver-Copper Steels

Magnification 100x

Magnification 500x

Figure 85.
Specimen 32

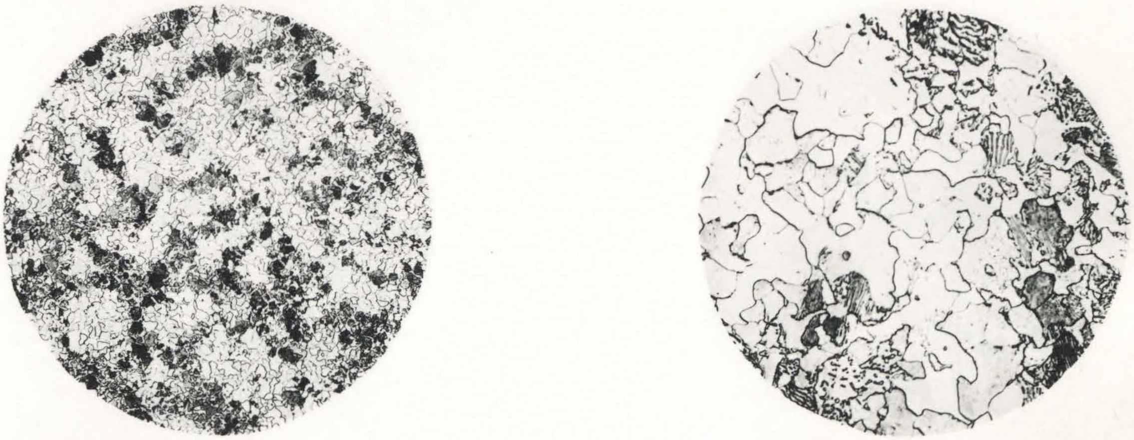


Magnification 100x

Magnification 500x

Figure 86.
Specimen 33

Microstructure of Forged and Annealed
Silver-Copper Steels



Magnification 100x

Magnification 500x

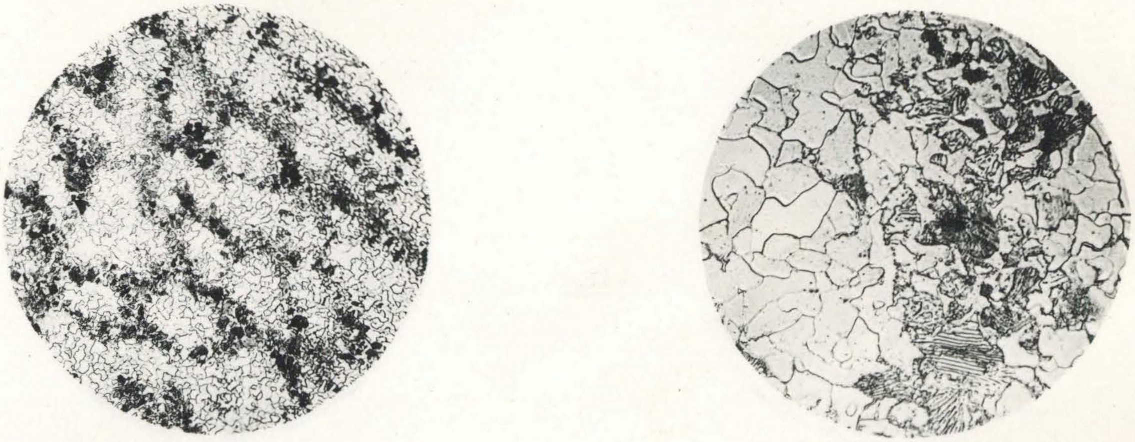
Figure 87.
Specimen 34

Magnification 100x

Magnification 500x

Figure 88.
Specimen 35

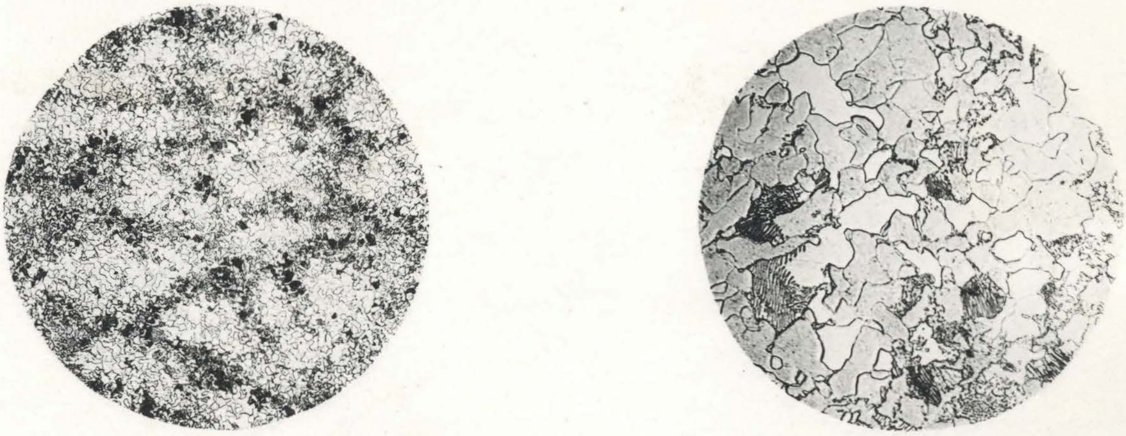
Microstructure of Forged and Annealed
Silver-Copper Steels



Magnification 100x

Magnification 500x

Figure 89.
Specimen 36



Magnification 100x

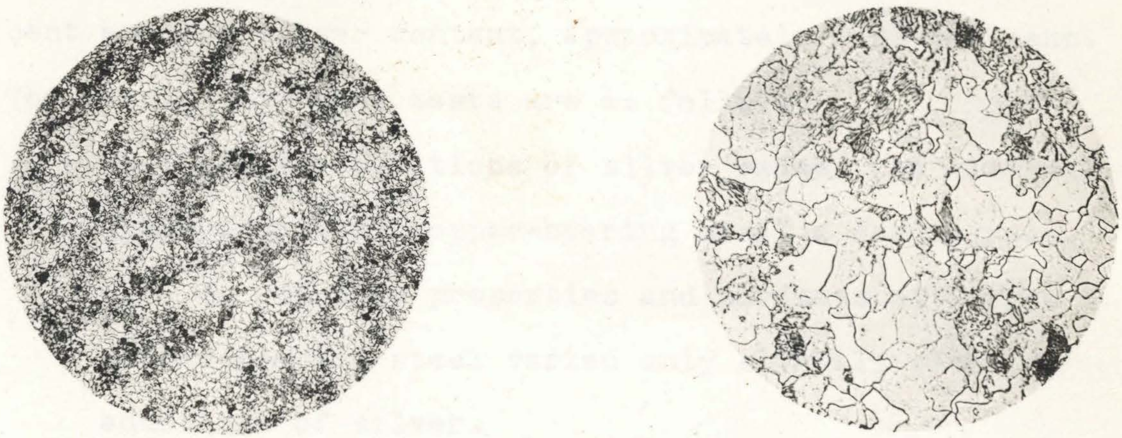
Magnification 500x

Figure 90.
Specimen 37

Microstructure of Forged and Annealed
Silver-Copper Steels

Magnification 100x Magnification 500x

Figure 91.
Specimen 38



Magnification 100x Magnification 500x

Figure 92.
Specimen 39

Microstructure of Forged and Annealed
Silver-Copper Steels

SUMMARY

1. The results of this investigation indicate that the solubility of silver in low carbon steels is approximately 0.02 per cent.

2. It was determined that by combining silver with copper before adding to steel, it is possible to alloy approximately 0.7 per cent silver with steel in the presence of 8 per cent copper.

3. The effect of additions of silver and copper on some of the properties of a 0.15 per cent and a 0.35 per cent carbon steel were studied. For this investigation, the copper content did not exceed approximately 2 per cent and the silver content, approximately 0.25 per cent. The results of these tests are as follows:

    a. The additions of silver raises the critical temperatures of copper-bearing steel a few degrees.

    b. Tensile properties and hardness of forged copper-bearing steel varied only slightly with additions of silver.

    c. The effect of additions of silver on the corrosion resistance of copper-bearing steels as determined by the water-spray test, is very slight.

d. The austenitic grain size of copper-bearing steel is not affected noticeably by the addition of silver.

e. No change could be detected in the microstructure of the forged copper-bearing steels after the addition of silver.

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