低炭素鋼に於ける粒の成長と物理的性質

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（はしがき）本文は私が昨年十一月當協會の講演會に於て講演致しました事の要領であります。實驗上の色々の細かい手續きやらそれから導き出した結論に到る徑路などに就きては之を一切本誌の末部に載せて置きました英文に讓ることに致しました。次の話の中に表はれて參りまする諸々の表や圖面は英文の部にあるものを其儘茲に引照致しますから故豫め左樣御諒承を乞ひたいのであります。

本題に掲げた者に類似の問題は既に大分古くから取扱はれたのでありまして、それに關する研究論文としては私が英文の部にビブリオグラフィーとして極く須要な代表的のもの丈けを撰んで幾つかを載せて置きました通りであります。此粒の成長に關する問題は最近、丁度私が米國に居りまする頃特に同國に於いて旺に論議されたものであります。乃てそれに關する論文も從て數多く出た譯でありますが其中、近頃の若手のゼー・ジェフリー博士が英國及び米國の兩學會に出した此種の論文は誠に徹底的で今迄不明として居つた粒の成長に關する諸現象を恰も名刀を以て亂麻を斷つと云つた樣な鮮さで説明をしました流石に評論の多い英國の學會も同博士の提言に對しては大體に於て反駁し得ない樣でありました、私の此の小さい研究は同博士が自身の研究結果を發表する以前より着手せられたものでありまして丁度一昨年から昨年に亘りて實驗したものであります。研究に費した時間が充分でなかつた上に外國で行ひましたことでありまする故に材料其他に就て不便なことも尠くなく從て研究がジェフリー博士の樣に到底徹底的なることを得ませんで遺憾に思て居る次第であります。

扱て本研究の大體の目的を申しますと次の様であります。研究に用ひました材料は直徑四分の三吋の低炭素鋼丸棒でありまして(其成分は重量百分率にて炭素〇・一一、硅素〇・二九、燐〇・〇三、滿俺〇・四七、硫黄〇・〇四)これを攝氏七百度以上約千四百度までの色々の溫度に定時間加熱し其間に鋼粒の成長が如何なる形に現れるか、又一定溫度に於て色々の異る長さの時間に加熱するとき鋼粒の成長が如何なる具合に行はれるか、言葉を換へて言ふと粒の成長が溫度と時間とに對して如何なる關係にあるかといふことを研究し、進んで此等の異なれる大さの粒が鋼の諸般の物理的性質例へば硬さ强さ伸び彈性率及び磁石性に對して如何なる影響を及ぼすものであるかと云ふ事を研究したのであります。此後者の粒の大さと物理的性質との關係、之は申す迄もなく吾々技術者に取て最も必要な事柄でありまするが著者の見る所に據りまするに從來の研究が此方面に於て充分明瞭でない様に思はれたのであります。是が抑も本研究の企てられた所以でありまして研究の主力も主として此邊に注がれたのであります。併し前申した様に時間の不足と材料其他の上の都合で、此方面に於て最も大切なりと思はるゝ諸種の動的强さ試驗を行ふ事の出來なかつたのを頗る遺憾と思て居ります。之は後日の機會を待ち度いと考へて居ります。猶右の外、粒の成長に關する研究としまして、加熱に供せらるゝ原鋼片の大小が粒の成長に如何なる影響を及ぼすものであるか、又異種の熱處理に據る粒の精粗も、之を定溫度に加熱處理すると一定の大さの粒にすることが出來るといふやうなことなども研究したのであります。此等の研究の結果は英文の部に於ける諸表、諸線圖及諸寫眞圖の示す通りなのでありますが是等に對する詳細の說明は一切玆に之を略し唯玆には此研究に由りて導き出された結論丈けを揭げ度いと考へて居ります。

イ　粒の成長に關する研究の結果

本試驗に供した試驗材料は前に示した様な分析結果を呈して居る低炭素鋼丸棒であつて、第二圖

(英文の部の Fig.2 を云ふ以下之に倣ふ)に示せる如き組織より成て居る。白つぽい部分がフェライト組織で、黒い部分はパーライト組織である。之を攝氏七百度以上約千四百度までの色々の溫度に夫々一時間加熱し、空氣中にて冷やした結果、粒の大さに變化を與へた。其結果は第四十二圖(英文 Fig.42)に於ける實線が之を表して居る。橫軸は各溫度を攝氏にて示し、縱軸は一萬分の一平方粍を單位として粒の平均の大さを表して居る。同圖に於て點線にて示したものは、前の實線にて示されたものと同樣に取扱はれたる各試驗片を更に前と同じ溫度に一時間加熱し、之を爐中に於て徐々に冷やしたものである。又鎖線で示した線圖は、攝氏九百五十度の一定溫度にて色々の異なる時間加熱し、後空氣中にて冷したときの粒の成長の有樣を示したもので、後の場合には線圖の縱軸は前の通りであるが、橫軸は加熱時間(上段の數字)を示してる。

實線が示して居る各試驗片組織の顯微鏡圖は、第三圖乃至第十六圖が之を表はし、點線の分に對しては第十七圖乃至第二十六圖が之を表はし、鎖線の分に對しては第二十七圖乃至第三十六圖が之を表はして居る。

右の通りの線圖及び顯微鏡圖などを精細に勘考した結果、次の樣な事柄が言ひ得られる。

一　本供試材料に於ては、攝氏八百度附近に於て、此材料が製出の際の展延其他其後の取扱ひのときに蒙れる幾分の內歪力に原因する粒の崩壞(英語に所謂 Recrystallization を結果の上より便宜上斯く譯して謂ふ)を生じ、九百度の溫度に近付くまで此傾向を增す。之と同時に他方面に於ては、或種の粒の成長が溫度の上昇と共に益々增大せらるゝを以て、顯微鏡圖に現はるゝ粒の大さには非常に大きいものと小さいものとが出來其大小の差異が溫度の上昇と共に著しくなる。

二　加熱溫度が攝氏九百度に達するや、以前に有して居た組織が全然破壞せられて、細微なるオーステナイトの粒を生じ、而して此者は加熱時間の增大と加熱溫度の上昇とに從て益々大きくなる。時

間の長短と溫度の高低とはオーステナイト粒の成長に至大の影響がある。

三 限界點を通過して冷却する際斯く成長したオーステナイトの粒が其儘アルファー粒に變移するものであるか、或は又全然別種の途によりて粒が發生するものであるかに就ては、多少の議論の存する所であるが、大體に於て大なるオーステナイト粒がより大なるアルファー粒を作り出すものであるといふ事は確實な事である。而して此事實は少くとも加熱溫度が千二百度(一時間加熱)に達するまでは確かである。

四 攝氏千三百度以上に於ては前と全く異なれる縞の様な組織が現はれる(第十四、十五、十六、二十六圖)。

五 冷却の方法は粒の大さに影響し、冷却を徐々にする程粒は大きい。

六 攝氏九百五十度にて夫々異なれる時間加熱し空氣中にて冷却したる結果は大體に於て粒の成長に影響がないと謂ひ得られる。

七 但し右の場合に於て加熱時間四時間以上の試驗片にありては粒の形に異狀あるものが現はれる。それは一個若くは二個、時々はそれ以上の小粒が他の大粒の中に全く包圍されて存在することがある(第二十九圖乃至第三十六圖)。併し是等の現象は爐の中で徐々に冷却した試驗片には決して現はれない(第三十七圖)。

八 本試驗の示す範圍に於ては試驗片の原形の大小は粒の成長に影響しない。

ロ 粒の大小と其物理的性質

一 ショア及びブリネルの兩硬度計を用ひて精細に試驗したる結果に據るに、本試驗の範圍に於ては粒の大小は(毎平方粍に就き六百乃至七千個の大さの粒につき)實際上殆ど硬度に影響がない。

二 本試驗の範圍に於ては最大破壞引張り强さは粒の大小には殆ど關係がない。唯空氣中で冷し

た鋼は爐中で冷したものより常に強い。故に粒の大小のみを知ては其強さの比較は云へない。以前にどんな熱處理を受けたかといふことを知て置かねばならぬ(第四十六圖)。

三　鋼の降服點(Yield point)は粒の小なる從て幾分高くなる。空氣中にて冷した鋼は爐中にて冷したものより常に其降服點が高い(第四十六圖)。

四　試驗片破壞後の斷面收縮は單位面積に於ける粒の數の增すと共に幾分增す、即ち粒の小さい程收縮は增す。爐中冷却の鋼は空氣中冷却のものより多分に收縮する。

五　攝氏千三百度以上の加熱に由り得たる縞狀組織は引張り强さに關係がない。唯降服點を著しく下げる。

六　粒の大小に對する磁性の變化に就ては、ヒステレシス損耗(Hysteresis loss)が粒の小さくなると共に幾分增大するけれども、パーミアビリティーに對しては殆ど影響が見えない。

七　右の樣な次第で粒の大小は强さ、硬さ、延性及磁性の如き物理的性質に就ては大體に於て其影響が極めて尠ない。

此試驗に於ては行ひ得なかつたが粒の大小に影響するものは諸種の動的强さであらう、衝擊試驗、繰返し荷物反覆荷物等に對する抵抗力は粒の大小に不尠關係あらうと察せらる。

以上が私の此研究に於て得たる主要なる結論でありまして、その之を得るに至りし徑路は前申した樣に玆に之を述べず一切英文の方に讓りました。猶終りに一寸附加へて置きたいと思ひますことは、直接當研究に關係ないことの樣ですが、私が硬度の試驗を行て居りますときに其試驗方法として一寸氣付いた事であります。それはショア硬度計を用ひて試驗するとき試驗片の表面の準備に就いて如何にしたら最も合理的で而も比較的平等な結果が得られるかと言ふ事であります。尤も之に就ては英國のグリンウッド(J.N. Greenwood)氏が千九百十八年第一號のインスティチュート・オヴ・メタル

スの會誌に於て(同誌六十六頁乃至六十七頁)硬度試驗に供する表面の狀態に就て氏の實驗の結果を擧げて居る。之に據ると試驗表面は大體に於て面の仕上の精粗に關係がない。最も粗いF號の鑢紙を用ひて仕上げた場合も、それより細かい一零號、二零號、三零號の他の三種のものを用ひた場合も先づ殆ど變りがないと謂て居る。私の實驗した所によると之は非常に澤山試驗したロングランに於て其平均數が大した變りがないと言ふことだらうと考へます。例へば自分が本試驗片を取り、之を九百度に加熱燒鈍してノーマルな狀態に置いた後、之を硬度試驗を行ふに適する樣三零番の鑢紙で研いて實驗して見ると、數回の試驗に九·〇から一一·五の間に變化する硬度數を得た。然るに今此試驗片を顯微鏡供試面を作るときと同樣に、アルミナとルージで研き上げ、それを試驗して見ると前よりも少ない變化の硬度數を得られる。例へば九·〇から九·五といつた樣な極く變化の範圍の少ない硬度數が現はれる(詳細は英文の第五表參照)。同一の材料を試驗してこんな違ひの出來るのは、前者の場合に於ては表面が鑢紙で磨かれた爲めに多數の溝渠が作られ、硬度計の落下錘が山の處に突當た場合と谷の處に落ちた場合とで反撥の模樣が異なるからである。之に對して後者の場合には、表面が鏡の樣に研き上げられてる故、落下錘が何處に落ちても大體に於て一樣の反撥を呈するのである。試驗の結果に不同なからしめ樣とするには、無論後者の表面が適して居る譯である。併しながら、かく研磨した表面には普通の狀態と異つた所謂非結晶質(アモーファス)の金質が蔽ふて居ると云ふことは夙にバイルビーの唱へた所でありまして、此金質は普通の組織である結晶質よりも硬いのであります。乃で今かく研磨したる表面を顯微鏡供試面を造るときと同樣に腐蝕して此非結晶質を除去し、金屬の正當なる組織を表面に發露する。而して前と同樣に硬度の試驗を行ふと、研いた儘のときよりも少ない値の硬度數を示す。而もその値は鑢紙で研いた表面よりも遙に變化の少ない比較的平等なものであります。例へば此場合には八·五から九·〇の間に變化する硬度數が得られます。(英文の第五表參照)然し此際若し腐蝕の時

間が餘りに長いと、腐蝕したものが腐蝕しないものよりも却て大なる硬度數を示すと云ふ様な結果になる。腐蝕液を硝酸一〇パーセントのアルコール溶液とすると十五秒から四十五秒までは腐蝕した試驗片が、常に腐蝕せざるものより小なる硬度數を呈するが、六十秒以上になると却て之と反對の事實を呈する。此反對の事實の起る譯は長き時間の腐蝕の爲めに、柔かきフェライト組織が多量に侵蝕されて、硬き質のパーライト組織を浮彫りの形に突出させて存する結果と考へられる(此等の詳細は英文の部に述べて置いた)。

玆には要領丈けを述ぶる積り故、或は之では說明が不完全ではあるまいかとの懸念も有りますが、要するに、硬度の試驗に適當した面の形成には、顯微鏡供試面と同樣に研磨の後、結晶組織が鮮かに現はるゝ範圍に於て腐蝕するのが、最も合理的で又平等なる結果を與ふる所以と信ずるのであります。普通行ふ鑢紙で磨いた面は縱令非常に多數の試驗を行たロングランに於ては等しき硬度平均數を示すかも知れないが、小數の實驗には著しく不同の結果を與ふる爲め宜しくなく、さりとてアルミナかルージの樣なもので研いた面は異常の金質を表面に作る故、之亦正當の試驗面と謂ふ譯に行かないのであります。

以上の事柄は極めて些細なことで、特別の注意を拂はないと容易く見逃して了ふことであります故、一般の實驗者には殆ど見逃されてる事實と考へます。試驗機の許す範圍に於て最も精確に又試驗の結果を最も合理的且平等ならしむるにはかゝる注意が又必要であると存じ、敢て玆に附加へた次第であります。前にも度々申しました通り之以上の事柄は英文の方に讓りまして玆には之丈けを以て終りと致します。

The Grain Growth of Low Carbon Steel and Its Relation to Physical Properties.

By

IHEI SUGIMURA.

I. Introduction.

Special attention has recently been paid by those who are concerned with the study or use of metal, especially in the United States, to many kindred subjects like the one here dealt with. In 1898 Dr. J. E. Stead[1] made public his exhaustive work on the crystalline structures of low carbon steel due to different heating, and on some of their physical properties, particularly on brittleness produced in iron and steel. Subsequently Dr. H. Fay and Mr. S. Badlam[2], in 1900, published the results of their experiment on the annealing effect upon tensile properties of low carbon steel containing .07 per cent carbon (heated at different temperatures up to 1247° C.) Since then extended study on various features of grain growth phenomena, especially in connection with greater or less state of strain, has been made by many workers, such as Joisten[3], Stead and Carpenter[4], Sauveur[5], Chappell[6], and others; and rather recently by Prof. H. M. Howe,[7] Dr. Zay Jeffries[8], Profs. Mathewson and Phillips,[9] Mr. D. Hanson[10] and others. Among them all Dr. Jeffries especially has made successful endeavor in carrying out his work and in summarizing all the results obtained by previous workers. He arranged them into a most comprehensive form, and drew out from them several important underlying principles which have vital concern with the grain growth phenomena. It is certain that his endeavor has

succeeded in throwing much light on the study of grain growth phenomena.

With regard to effects of varying grain sizes to different physical properties, however, it is the author's view that much which is now obscure and which should be made clear, appear still to be left untouched, or if touched upon, remains inconclusive. It is not inappropriate to say that study of grain growth phenomena is only made practically important by it having been found that the effects of the phenomena on the physical properties are not negligible. In other words, the correlation of various physical properties with grain sizes is of vital importance. This is the principal object of the present work and what was suggested by Dr. Jeffries in his recent papers.

II. General Remarks on the Experiment.

(a) Samples employed :

In order to obtain distinct granular structures, and to make easy the study on the present subject, and moreover to make the investigation as practicable as possible, a low carbon commercial round steel bar, three-quarters of an inch in diameter was used. Average result of the chemical analysis of this bar is as follows :

C 0.11 ;	Si 0.29 ;	P 0.03 ;
Mn 0.47 ;	S 0.04 in per cent.	

In order to ascertain the quality of the steel three test pieces each 5–3/4 inches long were sawed from different parts of the bar : one from the middle portion, and the others from each end of the bar ; and then from the end of each of these pieces, a piece one-half inch long was cut and used for microscopic study and hardness test. The longer pieces were put under tensile test. The results of these tests are represented in Tables I and II, and Fig. 41. With regard to scleroscope hardness test, precaution, an account of which will appear later (page 13) was taken. From results of all these tests we may say that the original bar is not abnormal, but rather homogeneous so far as these investigations (espeically

tensile strength) show. Moreover, all the examinations of microstructures made at different parts did not display any abnormalities. Fig. 2 is a representative photograph of them.

TABLE I. HARDNESS TEST FOR THE ORIGINAL STEEL BAR.

Position of specimen taken from bar.	Scleroscope number.									Brinell number.*			
	1	2	3	4	5	6	7	8	Mean.	1	2	Mean.	Number calculated.
One end	12.8	12.7	12.5	12.3	12.0	11.5	11.8	11.3	12.1	5.06	5.04	5.05	140
Middle	10.5	11.2	12.0	11.3	10.3	10.9	11.8	10.8	11.1	5.00	5.00	5.00	143
Other end	12.2	8.7	10.8	9.5	9.8	10.7	11.2	12.2	10.6	5.00	5.00	5.00	143

Total Average: Scleroscope no. 11.3;
Brinell no. 142.

TABLE II. TENSILE TEST FOR THE ORIGINAL STEEL BAR.

Position of specimen taken from bar.	Elongation in two inch gauge length, per cent.	Position of† facture occurred.	Contraction of area, per cent.	Yield point, lbs. per sq. in.	Modulus of elasticity, lbs. per sq. in.	Tensile strength, lbs. per sq. in.
One end	33.0	0.27	60.2	46,600	27.8×10^6	70,400
Middle	33.5	0.29	62.3	47,800	29.5×10^6	69,800
Other end.....	35.0	0.45	61.2	48,400	31.2×10^6	70,500
Average	33.8		61.2	47,600	29.5×10^6	70,200

It shows a normal polyhedral structure of about one-tenth per cent carbon steel, pearlitic structure scattered here and there, shown by dark

* Two diameters, each perpendicular to the other, were measured for the determination of the impression magnitude of the Brinell ball.

† This column has been added so as to make it possible to get proper judgment with respect to the amount of relative elongation in per cent. The position of fracture was measured from the nearest gauge mark, assuming the whole elongated gauge length as unit.

fields in the photograph. For future reference several heating and cooling curves due to time were recorded by the Leeds and Northrup Transformation Point Recorder for the present samples as shown in Fig. 40 which is a representative one.

(b) Furnaces used and other items:

For heating specimens, two kinds of electric resistance furnaces were used; the one for low heats up to 1100° C., was an ordinary type using nichrome wire, and the other, for higher temperatures above 1100°C., was a carbon tube type (Fig. 1). All heatings were made under ordinary conditions, i.e., in the furnace under atmospheric influence, taking due care to avoid too much free access of air from outside, by providing the furnace with a cover made sufficiently air-tight by plugging the hole carefully with asbestos wherever a free passage of air was noticed to occur, and thus undue oxidation of the specimen heated within was avoided. On employing the carbon tube furnace for higher heating, special precaution was taken, because it was feared that action of air on the tube at the high temperature might form a gas (mostly CO or Co_2 as the case might be) and affect the sample heated inside. To avoid such a contaminating action of the gas produced, a refractory tube of smaller diameter and longer than the carbon tube itself (about six inches longer altogether) was inserted in it, so that each end of the refractory tube might project outward about three inches from the carbon tube ends. (Fig. 1). After the sample had been placed at the middle position of the refractory tube, where the temperature was highest and uniform, some refractory harmless stuff was plugged into both ends of the tube, so as to prevent undue oxidation.

To show one of the characteristics of the furnaces used and to make clear the rate of the furnace cooling of the specimen heated there, cooling curves to each furnace are represented as Fig. 38 and Fig. 39, being conditioned by the room temperature (about 60° F.) where the furnaces are installed.

To acquire the measurement of temperatures, an ordinary platinum and platinum-rhodium thermo-couple was employed through the whole range of various heats. Thus, accurate comparative measurements are expected to be obtained.

All test pieces were obtained from the same one bar, each 5-3/4 inches long except magnetic specimens. After their respective heat treatment was completed, one microscopic sample of one-half inch length was sawed from the end of the specimen. This was also employed for hardness tests. The long portion left was put under tensile test, after machining into proper shape.

For revealing microstructures 10 per cent. nitric acid in alcohol was used as an etching reagent.

To measure the sizes of grains, Dr. Jeffries' method[8(a)] was applied.

On magnetic and other special kinds of tests, remarks will be made at the time when they are needed.

III. Study on the Grain Growth due to Heating at Different Temperatures and Constant Period.

(a) Procedure of the Experiment.

For the present research, three kinds of heat treatments were made at different temperatures, ranging from 700° C. to 1410° C. In the first place, each three specimens prepared as stated above, were heated at the same time to different assigned temperatures, keeping them there for one hour, and then cooling them in the air. All these treatments were performed in exactly the same way, for all samples of same heat. After the completion of this performance, they were divided into three groups, designating A, B and C respectively. Group A was submitted to various physical tests immediately without giving them any more treatment, results of which are indicated in Table III, and their microstructures in Figs. 3–16. For Group B, the second heating was made at the same temperature as its previous heating of one hour for each

sample, cooling in the furnace the second time as distinct from the previous treatment.

Group C was also heated again, but in this case they were all put in the furnace at the same time, and heated at 900° C. for one hour, cooling in the furnace down to the room temperature. This group consisted of samples heated up to 1100° C. inclusive, and heating was not extended up to a higher temperature than this as was the case in the other two groups.

TABLE III. AVERAGE GRAIN-GROWTH DUE TO HEATING AT DIFFERENT TEMPERATURES AND CONSTANT PERIOD.

Group.	Temperature, °C.	Average size of grains, sq. mm.	Number of grains per sq. mm.
Original.		.00047	2130
A	700.	.00051	1960
	730	.00051	1960
	800	.00025	4000
	850	.00022	4550
	900	.00014	7150
	950	.00055	1820
	1000	.00089	1120
	1100	.00124	807
	1200	00.124	807
	1335	00.210	476
	1410	.00383	261
B	700	.00057	1750
	730	.00057	1750
	800	.00039	2560
	900	.00036	2780
	1000	.0140	715
	1100	.00168	595
	1200	.00168	595
	1335	.00254	394

(b) Results of the above heat treatment.

Microscopic structures developed by different heats for A and B groups are represented in Figs. 3–26, and the grain growth due to various temperatures heated is shown diagramatically in Fig. 42. Up to 730° C. no group seems to have undergone any noticeable change, but at 800° C. some grains seem to have grown to a small extent, while at the same time some disintegrations of grains have occurred. When we see Fig. 5 we find many small disintegrated grains intermingled between larger original grains. They are more distinctly shown in Fig. 6 which has greater magnification than the former. This, the author thinks, although a state of growth has arrived among grains at this temperature, recrystallization has also taken place in some grains which were previously over-strained on account of rolling action or other causes. Thus, some rate of growth and a certain amount of disintegration have occurred at the same time, rendering the contrast of size of grains considerable and the average size of grains smaller. Moreover, cementite dissolved by ferrite during the heat, on cooling through the transformation range (See the transformation curve of Fig. 40) with fairly quick speed (especially when air cooled) might have tended to another disintegration of grains. This decrease in the mean size of grains was a little more pronounced at 850° C. for air cooled samples (Fig. 7) owing to some increase of recrystallization of grains which had been strained in the less degree than those already recrystallized at the lower temperature. At 900° C., the steel having already entered into gamma state, new austenitic crystalline arrangement ought to have occurred, and the old non-gamma grains were entirely effaced. During the heat above this temperature, grain growth manifests itself as austenitic growth, and generally the higher the temperature or the longer the duration of heating, the larger is this austenitic grain growth. As to the grain size of α iron obtained by cooling down from austenitic state, however, two different opinion prevail[7(c) & 8(c)]: whether the grain size be inherited from austenites

grains, or non-inherited from them, but naturally sprung up at the transformation point, and sizes of α iron grains depend mostly upon the manner of cooling from this new starting point. As the author's research has not extended far enough to enable him to criticize these two views and give a decision, he will not venture to say anything more with respect to this matter. Notwithstanding this, there seems to be no question, that if the rate of cooling is just the same, the larger the austenitic grain, i.e., the longer the heating or the higher the temperature of identical samples in most cases the larger will be α grains. Evidences of this fact are so abundant that no special references are needed. My experiment, of course, is concordant with this proposition. The grains in the air cooled sample heated at 950° C. have grown about three times larger than in the one at 900° C., and at 1000° C. about 6.5 times, at 1100° C. about 9 times, etc. (Fig. 42). For the furnace cooled samples, in every corresponding heat to the air cooled ones, grain sizes are larger than in the latter. This is certainly not because the former have been heated twice while the latter only once, but mainly because the former were cooled gradually in the furnace, whereas the latter were cooled rather quickly in the air. Specimens heated twice at a temperature lower than 900° C. may have gained a little more increase in grain size than the result obtained by slow cooling effect only by the second additional heating, but for above that temperature, previous conditions, whatever they might be, so far as they are not abnormal, do not throw any light upon the structures of samples thus obtained. Many previous workers have already given evidence of this statement.

In group C. of my experiment in which the specimens were heated at various temperatures the first time, and then heated together to the same temperature, 900° C., the same structure was obtained in all cases with no signs of difference of previous conditions. This, no doubt, will serve as an evidence for the above statement, and the larger growth of grains of the furnace cooled samples (group B.) in distinction to the

air cooled ones (group A.) can be said with certainty to be chiefly due to slower cooling.

Grain growth does not seem to occur between 1100° C. and 1200° C. either in the case of air or furnace cooling, while at 1335° C. both showed marked growth. But this markedly grown structure was not extended to the whole area, but rather confined within the region of the outer ring of the round etched surface of the specimen, the width of the ring being about three-sixteenths of an inch in both cases of air and furnace cooling. The inner part showed entirely different banded structure. Fig. 13 represents the region where the banded structure and polyhedral grains juxtapose for the air cooled sample. Fig. 12 shows outer granular structure for the same sample. Banded structure is indicated in Fig. 14 with higher magnification. Fig. 25 is a representative photograph of the granular structure of the furnace cooled sample. Measurements of grain sizes were made in the granular region in both cases. In the samples heated at 1410° C., banded structure was extended over almost the entire region of the surface, as shown in Figs. 15, 16 and 26, only for the air cooled specimen the outer thin shell being left as granular structure. Thus for the air cooled specimens, the grains were measured in such portions as showed granular structure, and the results of these measurements were tentatively added, as can be seen in the diagram, Fig. 42. In the furnace cooled specimen no such portion was found. With regard to the genesis of banded structure, the author thinks that it has come from the same cause as Widmanstätten structure*, although it is not so perfectly formed as the latter structure. Fig. 14 and Fig. 26 show close resemblance to this structure. It is quite certain that it is not what Dr. Stead called columnar structure, because the arrangement of banded ferrite is by no means normal to the outer surrounding surfaces. In consequence, we may conclude that it is not owing to gas escaping from inside the body, but to some other cause, which I ascribe to Widmanstätten's phenomenon.

* Sauveur's "The Metallography and Heat Treatment of Iron and Steel."

Such a high temperature heating as above 1335° C. is quite enough to make austenitic grains grow so large that on cooling them down through the transformation range, i. e., from gamma to non-gamma state, great resistance is encountered to the rejection of certain cementite dissolved in the large grains outside so as to render it possible to form large non-gamma grains; but makes its appearance between the cleavage planes of the small octahedra composing each grain, because the necessary time was denied for this dissolved cementite to reach the boundaries of the grains. The reason that the outer shell of the specimen shows granular structure can be explained in this way. Though care was taken, oxidation of the specimen could not be avoided, and in one case scale of about one-sixteenth of an inch was formed on the surface. Thus the decarbonization of the outer shell of the specimen could not be avoided and there is no doubt that some part was made almost free from carbon. Almost carbon free portion is not subjected to Widmanstätten's phenomenon, because there is no need to reject any such excess constituent during transformation.

With regard to group C nothing particular needs be said. As was said in simple words about the specimens before (page 8), by the second treatment all samples previously differently heat treated, showed no sign of particular variation in microscopic structure nor in strength test. We may conclude therefore, as is well known, that for identical materials any previous conditions, whatever they may have been, so far as they are not abnormal, e. g., internally oxidized structure caused by over-heating, etc., will be entirely effaced and become all alike in structure and physical properties.

IV. Study on the Grain Growth due to Heating at Constant Temperature and Different Periods.

To find out the effect of time with respect to grain growth at constant temperature, the author made eighteen specimens, sawing them from the original bar, each one-half inch long. Two of these were

used for each heating, the temperature being kept at 950° C. all the time, and the duration of heating varied from one to sixty-four hours. When the fixed period of heating arrived, the specimens were drawn from the furnace and allowed to cool naturally in the air. In this way a grain growth and time curve (Fig. 42 and also table) was obtained. Representative photographs for each heat are shown as Figs. 27–37. As the curve represents, for the present low carbon steel after four hours heating it already appears to have reached to some grain size of fairly steady equilibrium, and up to 32 hours heating, the grain sizes do not seem to have made any material development, while at the periods of 48 hours and 64 hours, they have grown to some extent.

In this treatment, rather remarkable structure which could not be found in other treatments was noticed. Fig. 35 indicates clearly this structure which consisted of grains including one or two, sometimes, more, smaller ones entirely within. This peculiarity of structure appears mostly to be due to the method of cooling. To assure this, the author made a test with a few other pieces which had been treated just like the specimens they were to be compared with, but in this case furnace cooled instead of air cooled. Fig. 37 represents one of these experiments, the structure of which is normal, in which all such peculiarity of grains disappeared and, in this case, grains were grown 1.6 times larger than those cooled in the air. Thus we may conclude with certainty that it is the manner of cooling which contributes mainly to the production of such peculiarity.

V. Does the Size of Original Specimen affect the Rate of Grain Growth?

To answer this question the author made two conical specimens as shown in Fig. 43 from the original bar. They were each machined exactly alike and put in the furnace side by side some distance apart with their respective ends reversed, in order to eliminate the effect due

to temperature difference in the furnace. They were heated at 1000° C. for one hour and then cooled in the furnace. Specimens obtained in this way were examined carefully with the microscope and practically no variation in grain growth was found at any part, i.e., at the smaller or larger end or at any inside section. Thus within the range covered by the results of this test, we may conclude that the size of the specimen does not affect the rate of grain growth.

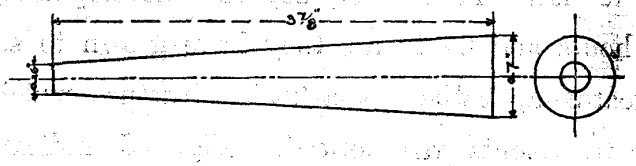

Fig. 43.—Conical specimen for the grain growth study.

VI. Physical Tests.

As to the physical tests for different grain sizes, three kinds of tests were made: (a) Hardness Test, (b) Strength Test, and (c) Magnetic Test.

(a) Hardness Test.

The most ordinary method of making this test is to use the scleroscope or the Brinell hardness tester. In this case both of them were employed. In spite of the careful measurement made, no special difference of hardness number in either kind due to grain size was detected, although differences were found yet they were irregular and did not seem to bear any special relation to grain sizes; moreover the degree of difference is so small that it can well be assumed to lie within the range of inhomogeneity of specimens and inaccuracy of measurement. Thus, so far as the hardness of metal is measured by these instruments, we can say that the grain size does not affect its hardness number within the limits of this experiment. There was, however, a

decided difference of hardness between air and furnace cooled specimens, the former invariably indicating higher value than the latter, but always less than original non-treated sample. As for example, results of heating at 1000° C. are shown in Table IV. Before leaving this subject some remarks will be of interest concerning some characteristics of the scleroscope test, which were noticed by the author during the test.

TABLE IV. HARDNESS TEST FOR DIFFERENTLY COOLED SAMPLES.

No. of specimen.	Temperature, °C.	Manner of cooling.	Scleroscope number.									Brinell number.*			
			1	2	3	4	5	6	7	8	Mean.	1	2	Mean	Number calculated.
16	1000	In the air	9.1	9.2	8.8	9.2	9.0	9.0	9.2	9.0	9.1	5.03	5.03	5.03	141
15	1000	In the furnace	8.2	7.8	8.2	8.2	7.8	8.3	8.1	8.2	8.1	5.20	5.20	5.20	131

It is a well known fact that the scleroscope hardness varies with the condition of the surface of the specimen to be tested, i. e., roughness or smoothness affects its hardness a great deal, and therefore the test is mostly made on a smooth and uniform surface. But there arises a question. Which is the most adequate smoothness of surface on which to apply this test? If we polish the surface as we do when preparing a surface for microscopic examination with the idea of acquiring the utmost smoothness, a more or less amorphous layer, which is harder than crystalline metal, is formed on the polished surface, and the result of a test on such a surface evidently differs from original crystalline phase of the metal to be tested, although the number of difference is often so small that the careless tester might easily overlook it. But for precise investigation, the author thinks, due attention should be paid to this point. Five specimens, each one-half inch long were sawed from

* Same remarks as Table I are applied here also.

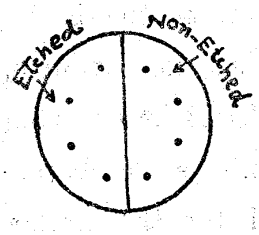

Fig. 44.

the same bar which had been heated at 900°C for one hour and cooled in the air. These specimens were ground and polished as in preparation for microscopic examination, and then half of each polished surface was etched with 10% nitric acid in alcohol for various periods and tested for hardness by the scleroscope at each corresponding position of etched and non-etched surfaces, as shown by Fig. 44.

The results of this test are tabulated in Table V.

TABLE V.

COMPARATIVE SCLEROSCOPE HARDNESS FOR ETCHED AND NON-ETCHED SURFACES.

No. of piece.	Duration of etching in seconds.	Etched portion.					Non-etched portion.				
		1	2	3	4	Mean.	1	2	3	4	Mean.
A	15	9.0	8.7	8.7	8.7	8.8	9.5	9.0	9.2	9.2	9.2
B	20	8.8	8.6	8.7	8.7	8.7	9.0	9.2	9.1	9.0	9.1
C	30	8.7	8.9	8.7	8.5	8.7	9.2	9.2	9.0	9.4	9.2
D	45	8.8	8.6	8.7	8.5	8.7	9.0	9.2	9.0	8.7	9.0
E	60	9.5	9.6	9.7	9.8	9.7	9.0	9.0	9.2	9.0	9.1

By glancing at this table we can see that until duration of etching is up to 45 seconds, the hardness numbers of an etched portion are invariably less than those of a non-etched portion, while at 60 seconds' etching the result is entirely the reverse. Although these numbers of differences are so small that they could easily be overlooked by a careless observer, yet the author never failed in detecting them, provided due care was taken, e. g., always setting the specimen tight between the holder and the anvil of the scleroscope so as not to admit any looseness of contact upon the anvil, the guiding tube of the dropping hammer being secured in a vertical position, the whole instrument

placed on a firm support which is as free as possible from any source of vibrations, or disturbing action, etc.

The fact that the non-etched portion shows harder numbers than the etched one can be explained as follows: the former is covered with amorphous metal[11(a)] which is hard and entirely different from the metal in its normal crystalline state, whereas in the latter this abnormal metal has been dissolved and the real crystalline structure of the metal to be tested, which is softer than the above amorphous phase, has been revealed. If etching be continued too long, however, as in the case of 60 seconds, Table V, the writer imagines that the well distributed, fine pearlitic structures stand in bold relief on the surface, and when the hammer of the scleroscope strikes the surface to be tested, the greater part of the energy of the falling hammer is absorbed by these pearlitic areas which are harder than the sunken ferrite structure.

As is tabulated, the hardness number of the etched surface does not vary through rather wide range of etching periods, from 15 to 45 seconds. Now if we prepare the surface to be tested by grinding with emery paper, as is frequently done, we find numerous scratches on the surface made by the emery particles. These scratches are the cause of the different values of hardness. For instance, the author prepared two surfaces, employing specimens A and C already used, by grinding with No. 000 emery paper, and tested them under the scleroscope, and found that a wider range of variations had taken place than in the above tests, e. g., in A sample, variations were from 9.0 to 11.2 and in C sample from 9.0 to 11.5, while in previous tests (Table V.) variations were all in less range.

From the results, the author is inclined to believe that in order to get the most appropriate result of hardness test from the use of a scleroscope, adequate preparation of the surface is of vital importance, and this surface is best acquired by polishing, just as in the case of preparing a microscopic surface, and then etched in the degree just enough to dissolve the amorphous layer formed on the surface and

reveal the real plane structure of the metal itself, taking due care not to over-etch.

I have to beg your indulgence for straying so far away from the subject here dealt with to discuss minute differences which are discovered by careful test and to propose a standard surface to be prepared for scleroscope test, for which the author himself is quite aware that much has been argued upon the fundamental principle of the instrument among authorities and its results are often underrated, in spite of its being handy and simple.

(b) Tensile Test.

In reference to this test, with the hope of finding out any minute relative differences which may exist due to variations of grain size, great care has been paid, especially to acquire modulus of elasticity, elastic limit if obtainable, yield point, contraction of fractured portion and maximum strength. Up to the yield point, load was applied with hand power as uniformly as possible, and at each successive definite load amount of extension was measured by a micrometer extensometer of one-ten thousandths graduation. After passing over the yield point, mechanical power was applied with slow speed up to the breaking point of the specimen. In this way results as shown in Tables VI. and VII. were obtained. Fig. 45 is the diagram plotted for contraction, yield point and maximum tensile strength against varying temperatures, and Fig. 46 is the same against different grain sizes, but here for the pieces heated at higher than 1335° C. in both cases of air and furnace cooling, results are not plotted because the partial or entire appearance of banded structure, rendered the determination of grain size impossible or meaningless. For each specimen, a load-strain diagram was plotted adjacent to the yield point, and was carefully studied with respect to the positions of the elastic limit and yield point. With regard to the former, however, as was expected, the precision of the appratus used was not great enough to detect the distinct point of improportionality, and moreover the inhomogeneity of the original sample was large

enough to conceal small variations due to different heat treatments, whereas the yield point was rather exactly determined. Therefore as to the elastic limit, nothing can be said here. As is shown by Tables II., VI. and VII. the change of the modulus of elasticity due to different heat treatments is well within the inhomogeneity of the original pieces, e. g., the original pieces give the values of from 27.8×10^6 to 31.2×10^6, while the results of different heat treatments give the values from 27.8×10^6 to 31.0×10^6 which lie obviously within the irregularity of the original material itself.

TABLE VI.—TENSILE TEST FOR GROUP A.

All samples were heated up to their assigned temperatures respectively for one hour and cooled in the air.

No. of specimen.	Temperature, °C.	No. of grains per square millimeter.	Elongation in two inch gauge length, per cent.	Psoition* tion of fracture occurred *	Contraction of area, per cent.	Yield point, lbs. per sq. in.	Modulus of elasticity, lbs. per sq. in.	Tensile strength, lbs. per sq. in.
3	700	1960	32.0	0.49	64.2	42,400	28.0×10^6	67,200
11	730	1960	35.0	0.44	66.7	42,700	27.9×10^6	70,500
8	800	4000	34.5	0.41	63.8	46,000	28.3×10^6	70,200
5	900	7150	34.0	0.49	64.3	45,000	28.8×10^6	70,000
16	1000	1120	32.5	0.45	61.0	44,100	28.8×10^6	69,400
18	1100	807	33.0	0.45	60.7	45,800	28.5×10^6	74,500
24A	1100	807	32.5	0.45	57.9	45,300	29.7×10^6	69,500
23	1200	807	32.5	0.47	56.2	45,800	28.5×10^6	69,300
24	1335		26.5	0.30	51.1	33,200	28.7×10^6	70,700
26	1410		30.0	0.38	51.7	34,500	28.1×10^6	70,500

* Same remarks as Table II. are applied here.

Now what can be said for other properties, i. e., for maximum tensile strength, for yield point, for contraction, etc.? As the number

TABLE VII.—TENSILE TEST FOR GROUP B.

All samples were heated twice up to their assigned temperatures respectively for one hour, and for the first heat, cooled in the air and for the second, cooled in the furnace.

No. of specimen.	Temperature, °C.	No. of grains per square millimeter.	Elongation in two inch gauge length, per cent.	Position of fracture occurred.*	Contraction of area, per cent.	Yield point, lbs. per sq. in.	Modulus of elasticity, lbs. per sq. in.	Tensile strength, lbs. per sq. in.
4	700	1750	40.0	0.45	67.5	41,200	27.8×10^6	63,400
12	730	1750	38.0	0.40	68.0	40,000	29.3×10^6	62,900
9	800	2560	37.0	0.49	64.3	42,500	29.4×10^6	66,300
6	900	2780	35.0	0.31	64.3	41,000	30.2×10^6	65,900
15	1000	715	32.5	0.48	61.6	39,100	29.3×10^6	65,700
19	1100	595	35.0	0.46	61.0	36,100	27.8×10^6	65,500
28	1100	595	33.0	0.45	59.8	39,600	28.2×10^6	65,700
22	1200	595	32.5	0.49	60.7	40,400	28.3×10^6	66,300
29	1200	595	32.0	0.49	59.8	40,200	29.9×10^6	66,400
25	1335		35.0	0.43	61.2	42,600	30.1×10^6	72,200
30	1335		36.0	0.25	60.5	36,700	27.9×10^6	64,700
27	1410		32.5	0.43	60.5	30,400	31.0×10^6	63,200
31	1400		34.0	0.39	59.8	35,300	28.9×10^6	64,800

* Same remarks as Table II. are applied here.

of pieces tested was not large enough; and also as the range of variations of grain sizes was not wide enough, and moreover as the material used in this test was not homogenous enonugh, because it was a commercial bar and not particularly prepared steel, although the test made at the three portions of the original bar shows it rather to be homogenous (see Table II.), yet regarding other portions in between, we can not be sure of the non-existence of accidental abnormalities; small differences which may be expected to exist in the same material due to

varying grain sizes have not been conclusively decided by these tests. The greatest defect of the strength test lies in the fact that it invariably represents the results of the weakest point in the whole portion of the test piece. Therefore we may state that as far as irregularity of samples is greater than the differences which are caused by varying heat treatments or different grain sizes or unlike structures, effects due to the latter causes are in most cases entirely concealed by the former irregularities. In this way, the ultimate tensile strength of the weakest point, as is clearly shown in Fig. 45 and Fig. 46, is very irregular, and there does not appear to exist any special variations due to different grain sizes and heat treatments, except that air cooled samples are invariably stronger, about 5,000 lbs. per sq. in., than furnace cooled ones. We may therefore conclude that the grain size does not affect the tensile strength within the limits of the test. If the amorphous cement theory[11(b)] of the grain boundary is true, it is natural to presume that the larger number of grains is stronger than the smaller, assuming either the material or size of the specimen to be identical; because the former contains a larger amount of amorphous metal than the latter and, as is well known, amorphons state is harder and stronger than crystalline structure.[12] Thus the author's statement made above, at first sight appears to be contradictory to the amorphous theory just mentioned, but he thinks it is not necessarily so. The inference is that difference of strength between coarse and fine grains is so small that the inhomogeneity of material conceals it entirely.

Banded structure does not seem to affect tensile strength to any extent.

With respect to yield point due to different heating, as is represented by Fig. 45, a marked descent is noticed at higher temperatures than 1335° C., while at lower temperatures no special variations are found, except that air cooled specimens invariably show higher yield point than furnace cooled ones.

If we put the yield point, however, against number of grains per

square millimeter, as is shown in Fig. 46, although points thus plotted are not situated with exact regularity due to grain sizes, yet not so much extent of irregularity was noticed as when tensile strength was measured, we find that yield point increases slightly for the furnace cooled specimens and very alightly for the air cooled ones with the decrease of grain size, i. e., the finer the grain the higher is the yield point to a small extent.

As to the percentage of contracted area after fracture, differences due to varying temperatures and grain sizes are a little more marked than in the other cases. Pieces heated at higher temperature than 1000° C. seem to decrease their percentages of contractions at a greater rate in the air cooled ones than in the furnace cooled. This fact is quite opposite to that in the other cases, where air cooled pieces mostly showed higher values than furnace cooled ones. From the diagram represented in Fig. 46 we may state that the percentage of contraction increases with fineness of the grain within the limits of the experiment made, and the manner of cooling does not appear to affect the amount of contraction so much as in the other cases. Banded structure obtained by high temperature heating, at least in the present test, gives the smallest percentage of contraction.

As is well known, local elongation is greatest at the proximity of the fractured portion, whence in both directions along the piece, it diminishes with increasing distance. Position of fracture therefore affects the amount of elongation in per cent to a great extent and maximum percentage of elongation is obtained only when fracture has taken place exactly at the centre between the prefixed gauge marks of the specimen. Actually, however, it is seldom that fracture occurs just at this central position, but ordinarily more or less distant from it, and it is by no means infrequent to have breakage occur in the vicinity of the gauge marks. Thus, elongation can never be constant within reasonable range, even in the same material, mainly because of the occurrence of fracture at varying positions. This is the reason why the

author has not taken elongation into consideration for the study of physical properties which are not expected to affect grain size to any considerable extent.

(c) Magnetic Test.

For this purpose the Koepsel permeameter was used. The author is aware that it is not suitable for acquiring absolutely accurate results and yet he adopted it on account of its simplicity in many points, expecting that for a relative test such as the present one, by adequate care being taken, relative differences due to grain sizes would not be difficult to obtain. In this way two kinds of magnetic properties with regard to different heat treatments and grain sizes were studied: the first is magnetic induction due to varying magnetizing force to plot normal induction curves (B-H Curves), the second is hysteresis property of different samples. As the samples to be employed were exhausted, the number of pieces used for the present magnetic test were only four in all. They were heated at 730° C., 850° C., 950° C. and 1100°C. respectively for one hour, and cooled in the air just alike, and then machined into the exact shapes, 5 millimeters square and $8\frac{1}{2}$ inches long, so as to fit the permeameter, special care being taken when machining not to put any abnormal stress on the specimens. To get most reasonable relatively accurate results and to eliminate any source of errors as far as possible, great care was taken in preparing specimens and performing tests For the first, however, among different specimens, variation of magnetic induction B in reference to the same magnetizing force H was so small and irregular, that no particular relation appears to exist with regard to the grain size, etc. Thus the author is led to conclude that within the limits covered by the present test, different heat treatments, or varying grain sizes practically do not affect permeability.

For the second hysteresis property, however, some regular relation was found due to different heat treatments and grain sizes. In Table VIII. each relative hysteresis area for different heats and number of

grains per cubic mm. are shown, and in Fig. 48 a curve of relative hysteresis areas against number of grains per unit volume is plotted. Here, relative hysteresis area means the number acquired by dividing a certain given hysteresis area with the smallest one, provided, of course, each hysteresis curve is plotted with the same scale. As a typical example, a hysteresis curve of the specimen heated at 1100° C. is shown in Fig. 47, which represents the smallest area of hysteresis loop in all of the specimens tested. The shape of the curve of the other three specimens is almost identical, merely showing small differences of loop areas.

TABLE VIII.

GRAIN SIZE AND MAGNETIC HYSTERESIS.

No. of specimen.	Temperature, °C.	Number of grains per cubic millimeter.	Relative area of hysteresis loop.
M1	730	86,800	1.078
M2	850	306,900	1.162
M3	950	77,700	1.020
M4	1100	22,900	1.000

Integrating the areas enclosed by these loops with the aid of a planimeter, and denoting them with a unit of the smallest area obtained by the 1100° C. specimen, and then plotting them against number of grains per cubic unit of volume, we acquire a diagram as represented by Fig. 48. By looking over the curve thus obtained we are able to consider that magnetic hysteresis changes in the same direction as number of grains per unit volume. For the comparatively high value of magnetic hysteresis of specimen M1 due to its grain number, the author infers that it is not under normal condition, but is strained to a certain extent and has not been released from that state of strain, even though it was heated up to 730° C. (page 7), as is well known, strained iron gives higher magnetic loss per cycle than the same iron in normal state[13 & 15]. In the same way, speciman M2 which was heated

at 850° C., for one hour still seems to possess some amount of stress gained during previous working. Thus if the author were permitted at this moment to theorize regarding the above relation, he would say that magnetic hysteresis loss per cycle is proportional to number of grains per unit volume. He is quite aware that it is not at all scientific to form such a conclusion based on such scanty results as indicated by the above tests.

VII. Summary.

Before entering upon the discussion of the results obtained above, it will be more convenient to give a summary of them at the present time.

(a) On the Grain Growth.

1. For the present sample (commercial low carbon steel bar), recrystallization of structure seems to start in the vicinity of 800° C. and increases in amount with the rising temperature to somewhere near the transformation point of 900° C., providing in all cases heating was continued for one hour; while at the same time growth of certain grains is more pronounced with increasing temperature, eventually causing grain size contrast more and more marked up to near 900° C.

2. On reaching 900° C., previous structure is entirely destroyed and very minute austenitic grains spring up, growing larger and larger with prolonged heating or with increasing temperature. Both duration and intensity of heat are vitally concerned with austenitic grain growth.

3. Though it is not ascertained whether these grown austenitic grains are inherited just as they are or entirely different grains should spring out on cooling down from the transformation point, it seems to be certain that within limits the large austenitic grains yield larger alpha grains. This is true at least up to 1200° C. heating for one hour.

4. Above 1300° C. some banded structure which is entirely different from others appears.

5. Manner of cooling affects grain size and structure; slower cooling yields larger and well defined polygonal structured grains. (See micro-photographs).

6. When air cooled, different periods of heating (from 4 to 32 hours) at 950° C. do not seem to affect average size of grains. Heating for 4 hours increases average size about one-half more than heating for one hour, and heating for 64 hours increases about two-fifths than for 32 hours heating.

7. In pieces heated longer than 4 hours and air cooled, a peculiar structure with grains which wholly include within them one or two, and sometimes more, smaller grains was found. But when the pieces were cooled in the furnace, most of this peculiarity disappeared and normal structure was restored.

8. The size of the original specimen does not affect the grain growth within the limits of the experiment.

(b) On Physical Properties (due to Grain Size).

1. Scleroscope hardness test should be applied on properly etched surface of the specimen (not deeply etched). A ground surface gives irregularity of hardness number, and a polished surface displays the hardness of the different state of the metal to be investigated.

2. Careful investigation of both kinds of hardness tests, scleroscope and Brinell, shows scarcely any difference due to grain size. Practically, hardness does not seem to be affected by grain sizes within the limits covered by the test (grain sizes from 600 to 7,000 per square millimeter).

3. Within the test limits maximum tensile strength is practically independent of varying grain sizes. Air cooled steel is invariably stronger than furnace cooled. Therefore grain size alone does not tell its strength correctly, even in identical metal, unless the previous treatment is known.

4. Within limits, yield point increases very slightly with nubmer

of grains per square unit of area. Air cooled steel always shows higher yield point than furnace cooled.

5. Contraction of area after fracture changes in the same direction as number of grains per unit area, i.e., increases with fineness of grains. Furnace cooled steel contracts more than air cooled.

6. Banded structure acquired by heating above 1300° C. does not seem to contribute to tensile strength except in the marked dropping down of yield point.

7. With regard to magnetic properties, permeability does not seem to change with any regularity in the present test due to varying grain sizes, but hysteresis loss per cycle slightly increases as grains become finer.

VIII. Notes on the Correlation of the Grain Size with Physical Properties.

The importance of such information needs no discussion, the only question is to investigate in what way the grain size affects various physical properties. Before going into the discussion of low carbon steel upon which the present work has been made, we will just consider it with another metal, such as brass, of which Profs. Mathewson and Phillips[9] made a great deal of study. In Fig. 49 is represented a curve which has been drawn by the author of this paper from data given in Tables V (a) and V (B) and a diagram of Fig. 4 by them.

From this curve we understand that tensile strength and scleroscope hardness increase with number of grains per sqnare unit of area, and as to contraction of area the same statement can be applied up to 1,000 grains per square millimeter, and according to their statement the grain size is not the only factor which determines the value of any given property. Elongation was disregarded in the diagram of Fig. 49 from their data owing to the same reason which was described in page 20. With regard to the grain size and tensile strength, they say, by showing

results represented in Table IX, that with due allowance for errors in counting, measurement of grain size is more sensitive in detecting variations in strength properties than tensile tests themselves.

TABLE IX.

SUMMARY OF PROPERTIES AFTER HALF-HOUR ANNEAL AT 550° C— BRASS CONTAINING 66.56 PER CENE. COPPER, 0.26 PER CENT. LEAD, 0.08 PER CENT. IRON.

Initial reduction, per cent.	Elongation in 1 in., per cent.	Reduction of area, per cent.	Tensil strength, lbs. per sq. in.	Sclero-scope.	Grains per sq. in. at 85 diameters.
20	72	59.5	46,739	10	55.5
50	73	62.0	47,100	10	67.2

Quite recently Messrs. W. H. Bassett and C. H. Davis[14] also reported on the results of Brinell hardness tests of cartridge brass that the fineness of the grain size increases Brinell hardness. Thus for brass there is no doubt that important relations exist between varying grain size and statical strength test and hardness properties.

For low carbon steel, however, it does not appear that the grain size has any vital important relation upon either statical strength or hardness properties, according to the present investigation. There is no doubt that fine grain structure should be stronger than coarse grain mainly because more grain boundaries, which consist of amorphus state of metal, are found in the former state than in the latter. And the difference of statical strength is mostly dependent upon the difference of the amount of amorphous metal existing in the metals to be compared with. This difference, however, is not great, in fact it is practically negligible, even though the existing amount of amorphous state at least in case of low carbon steel, such as the one here dealt with. This statement is also justifiable in case of very low carbon steel, as indicated by Dr. Stead.[1] When subjected to strength test, unavoidable

failure of test pieces occurring at the weakest portion of the whole body, so long as absolutely homogeneous metal is not practically obtainable canceals and covers all the differences due to varying grain sizes, especially in a more pronounced degree in case of commercial steel. Consequently the grain size is not important so far as above kinds of properties and metals are concerned. With respect to dynamic properties, however, such as repeated or alternating stresses, or impact resistance, it is an entirely different proposition. For the resistance against these kinds of forces, Stead, Beilby and Rosenhain explained fully and clearly, and what is described in Rosenhain's "Introduction to Physical Metallurgy," 1915, will serve to make them clear:—

> "On the other hand, under both shock and fatigue tests a coarse structure, even in a simple metal, gives unsatisfactory results. The reason is easily understood, for the crystal boundaries act as a species of strengthening skeleton; at each boundary a crystal is supported by its neighbors, since a slip-band, for example, must change its direction—often in two planes—where it passes from one crystal to another, and if the stresses at work are such as to favour slipping in one of these directions, they will not be so favourable for slip in the other, so that the weakness of one crystal will be balanced by the strength of another. Where the crystals are large, single surfaces of slip or cleavage extend unbroken through relatively large areas, and fracture—particularly under shock or fatigue—may be brought about under conditions which a finer grained structure would have resisted." (pp. 274–275).

As to some probable relation regarding corrosion problems, Jeffries[8(b)] summarized the results of previous workers as follows: other conditions remaining the same, it would seem that the greater the quantity of amorphous material present, the greater would be the rate of corrosion.

The author made experiments concerning relative etching speeds of fine and coarse grains on the same samples employed in the present

work when etched by 10% nitric acid in alcohol, and invariably found that for the equal area of the etching surfaces the former loses its weight more quickly than the latter. As for example, one set of results obtained is shown as follows:

No. of specimen		12	19
Temperature heated.....		730° C.	1100° C.
No. of grains per sq. mm.		1750	595
Weight of specimen after etching 20 seconds and completely dissolved....			
Amorphous layer formed on the surface by previous polishing	in grams	28.83085	29.0904
Weight of specimens after etching the equal area of the surfaces 20 seconds more	in grams	28.8293	29.0892
Loss in weight of specimens du to same period of etching.....	in grams	.00155	.0012

Rosenhain[11(b)] studied on relative volatilization of fine and coarse grained structures of pure metals to verify his hypothesis regarding the amorphous cement theory of grain boundary, and showed us that at high temperature fine grain structure volatilizes more readily than coarse.

In Jeffries' paper Mr. F. C. Thomson mentioned his brief summary of the results obtained after studying for some time the relation of grain size and physical properties, which he had not yet completed at that time, as the following:

> "The material I used for the purpose was an extremely pure crucible steel containing 0.049 per cent. of carbon and 99.84 per cent. of iron. For this material (a) the electrical resistance is a linear function of the number of crystals per unit length; (b) the magnetic permeability decreases and the cœrcive force and hysteresis loss per cycle increase as the grain size becomes finer. The maximum induction and the remanence are unaffected by the crystalline size;

(c) the maximum stress is increased, but the elastic limit is approximately proportional to the cube root of the number of crystals per unit length. (In the case of a mild acid open-hearth steel containing 0.26 per cent. of carbon and about 0.5 per cent. of manganese, the elastic limit is more nearly proportional to the actual number of crystals per unit length. Here, of course, two factors are involved, both affecting the elastic limit in the same direction; the actual size of the individual grains of pearlite, and also at least equally, the degree of fineness of the carbide plates within those grains)."

The present work is really a part of Mr. Thomson's endeavor, the complete results of which, with their data, do not appear to have been published and which the author, believing they would render the subject conclusive, desires to see done at an early time.

Acknowledgment.

At the close of this paper, the auother takes pleasure in acknowledging here with sincere thanks the kindness extended by professors and instructors of the Massachusetts Institute of Technology, and especially to Professor H. O. Hofman for his favor, to Professor C. R. Hayward for suggesting work and for continual help in furnishing samples, useful apparatus, etc.; to Professor H. Fay for his continual interest in the subject and for valuable suggestions; to Professor H. W. Hayward for aid in the mechanical tests; to Professor F. A. Laws for aid in the magnetic tests; and to Professors C. L. Norton and G. B. Wilkes for aid in the heat treatment.

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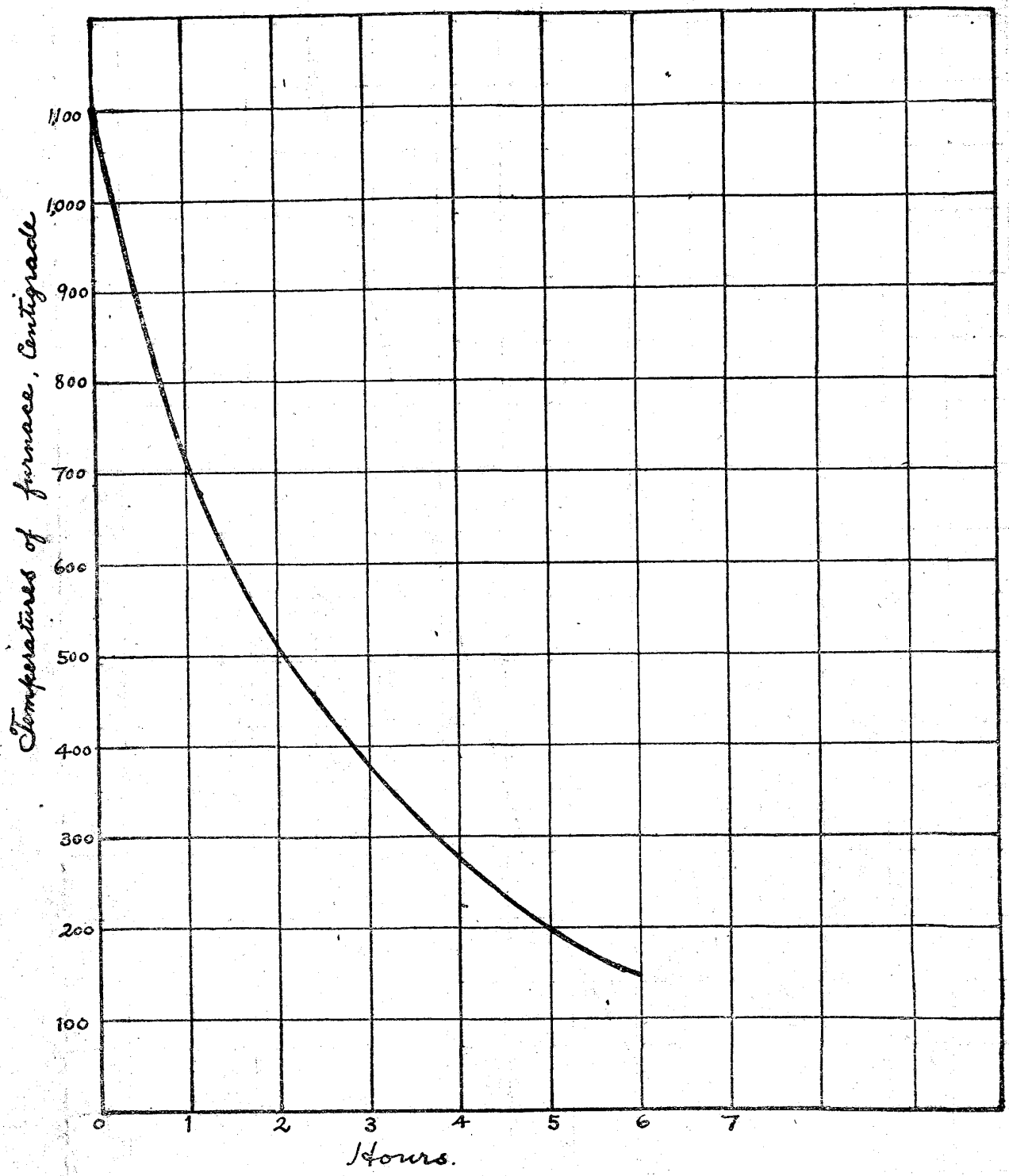

Fig. 38.—Cooling curve of the electric resistance furnace using nichrome wire.

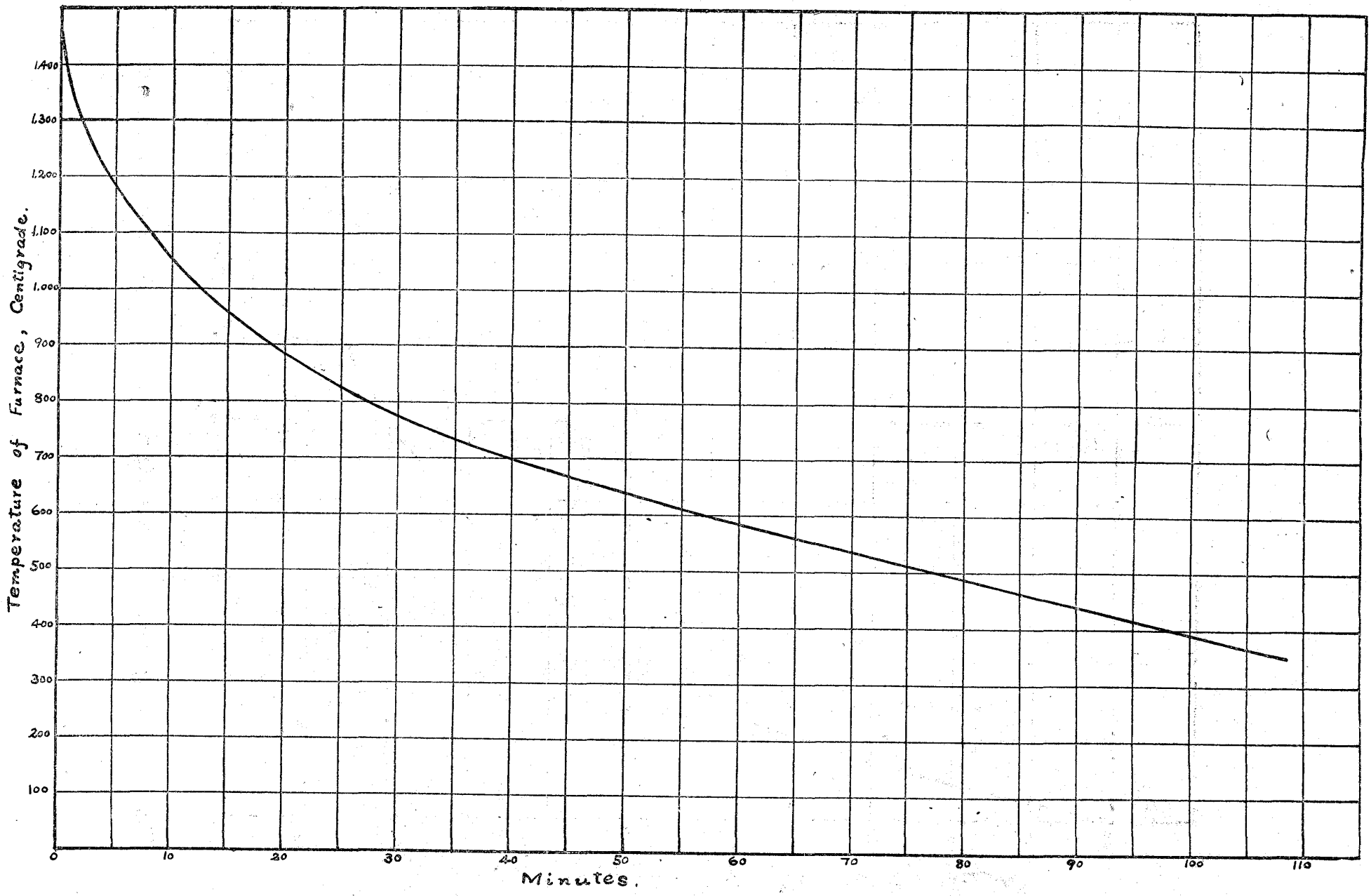

Fig. 39.—Cooling curve of the carbon tube electric furnace.

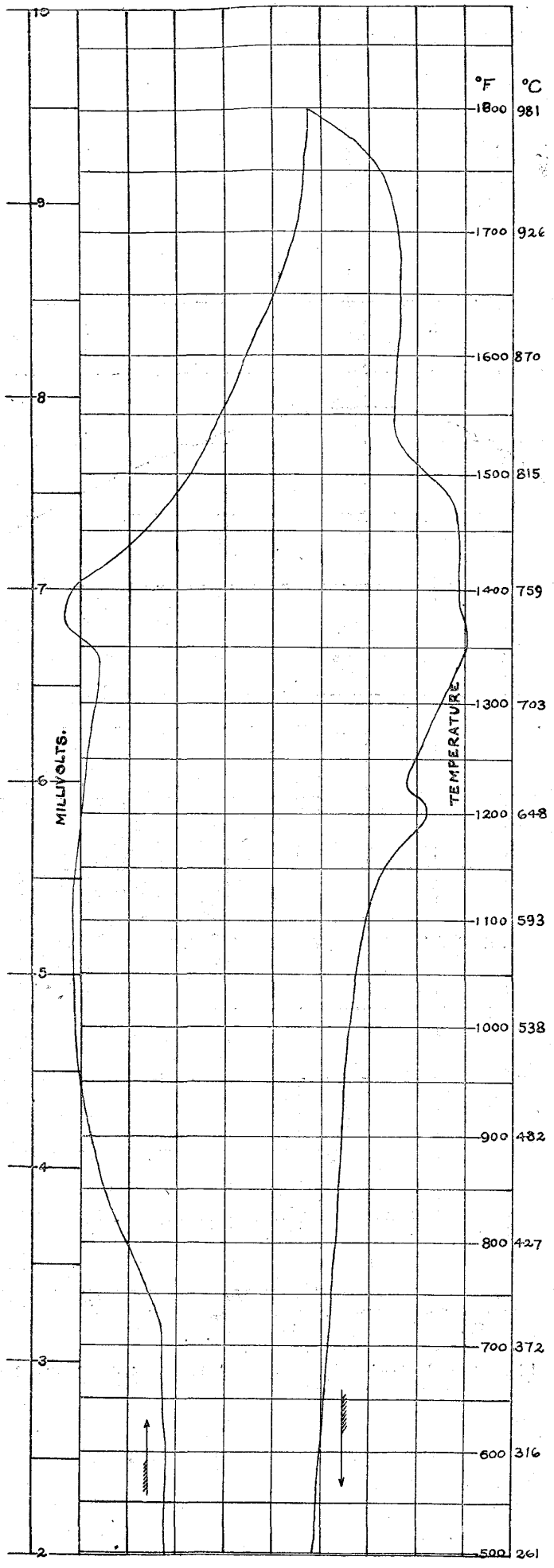

Fig. 40.—Heating and cooling curve of the steel.

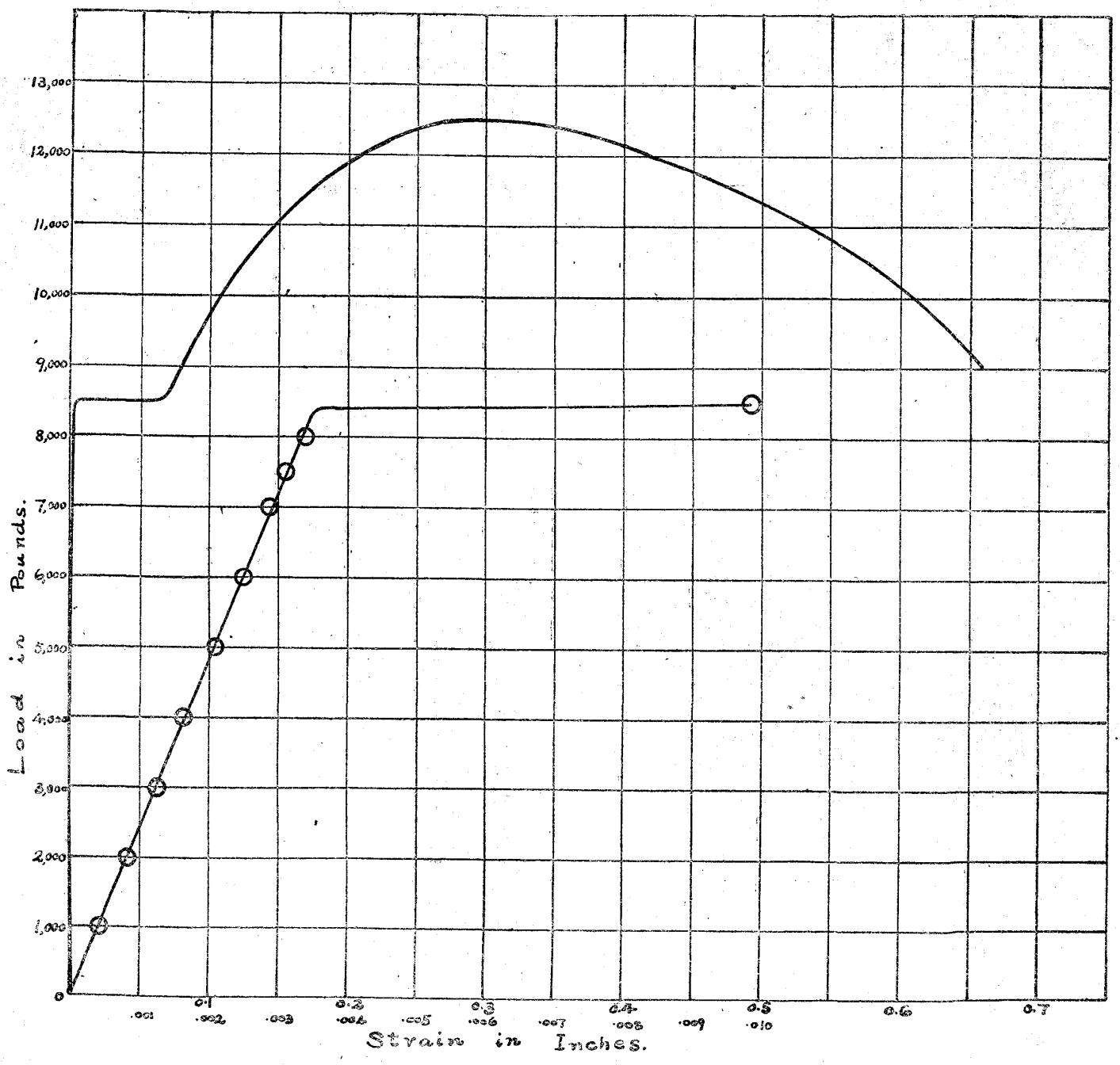

Fig. 41.—Load-strain diagram of the original steel.

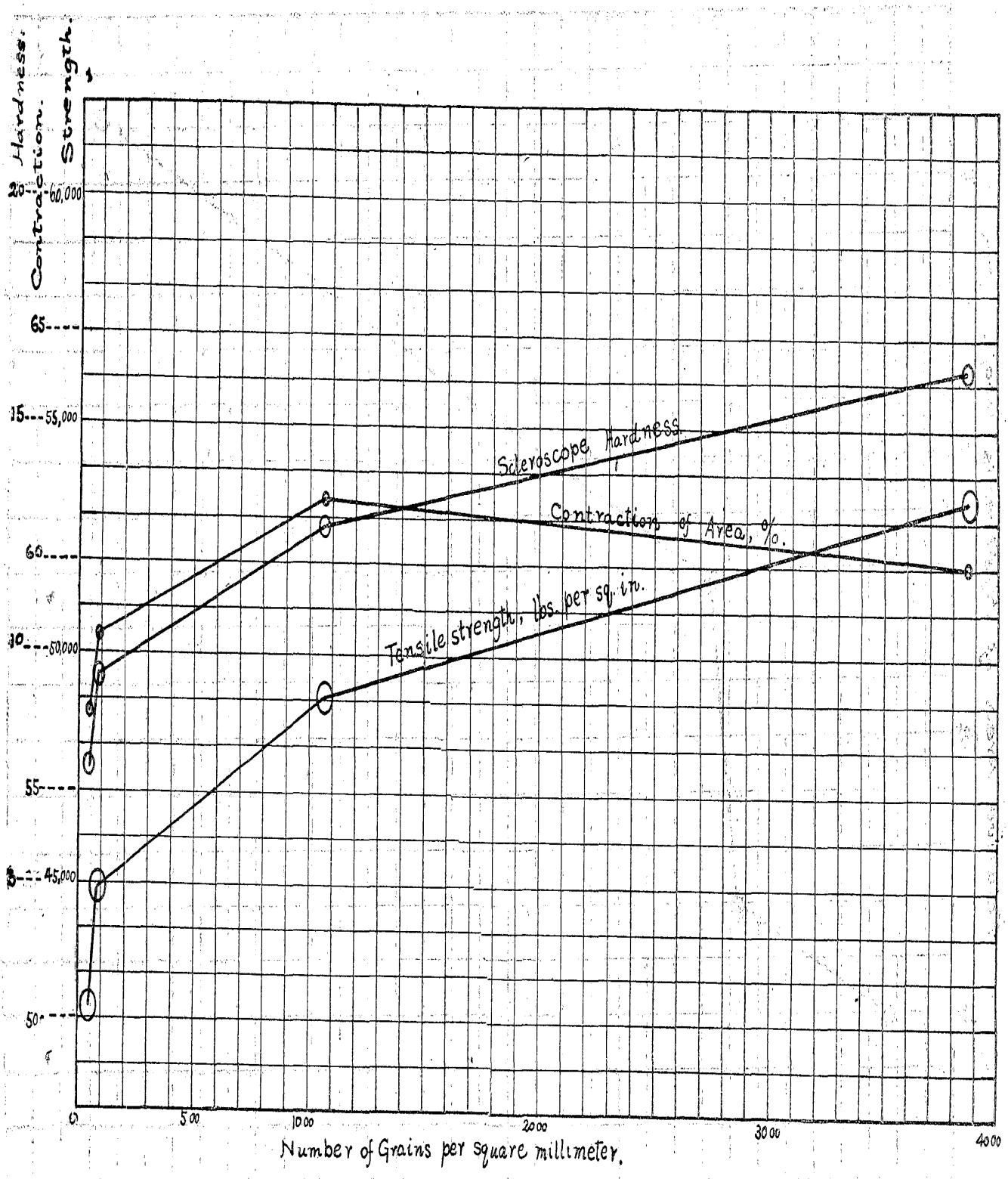

Fig. 49.—Tensile strength, contraction of area and sclerоscope hardness of brass containing 66.65 per cent. copper, 0.30 per cent. lead, and 0.08 per cent. iron; previons reduction 50 per cent.; and different grain growth acquired by different heating of 30-min. period.

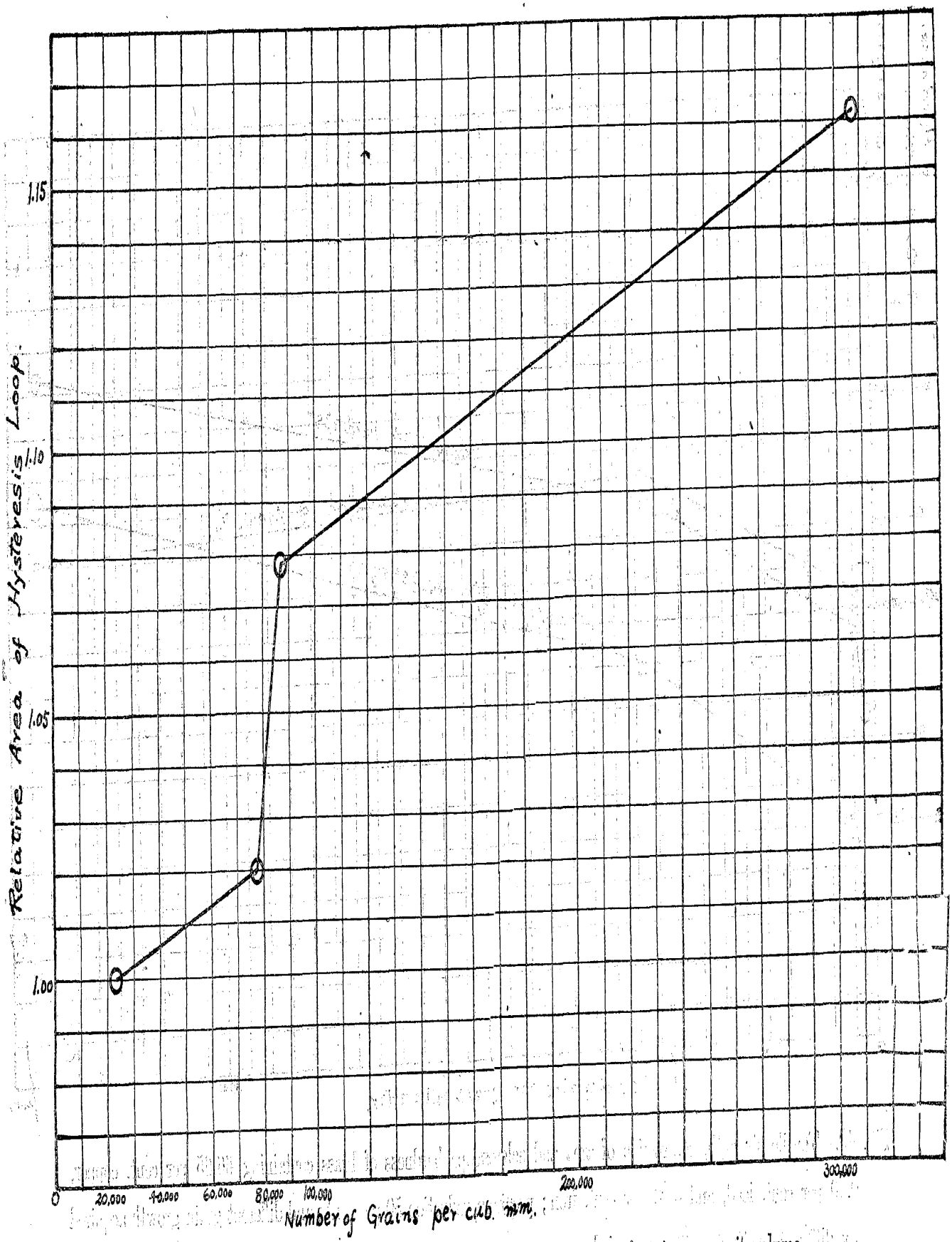

Fig. 48.—Relation between hysteresis loss per cycle and number of grains per unit volume.

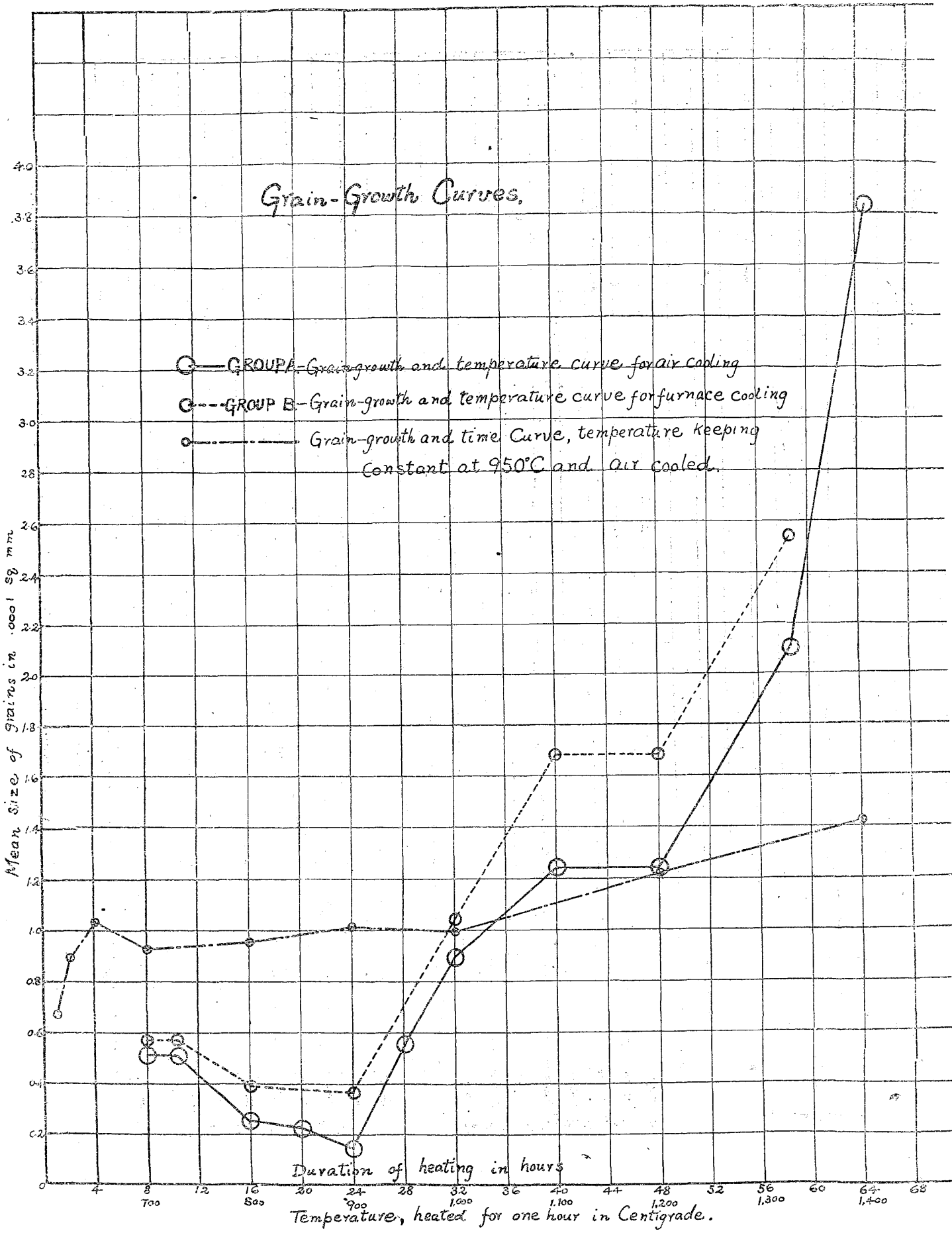

Fig. 42.—Grain growth curves.

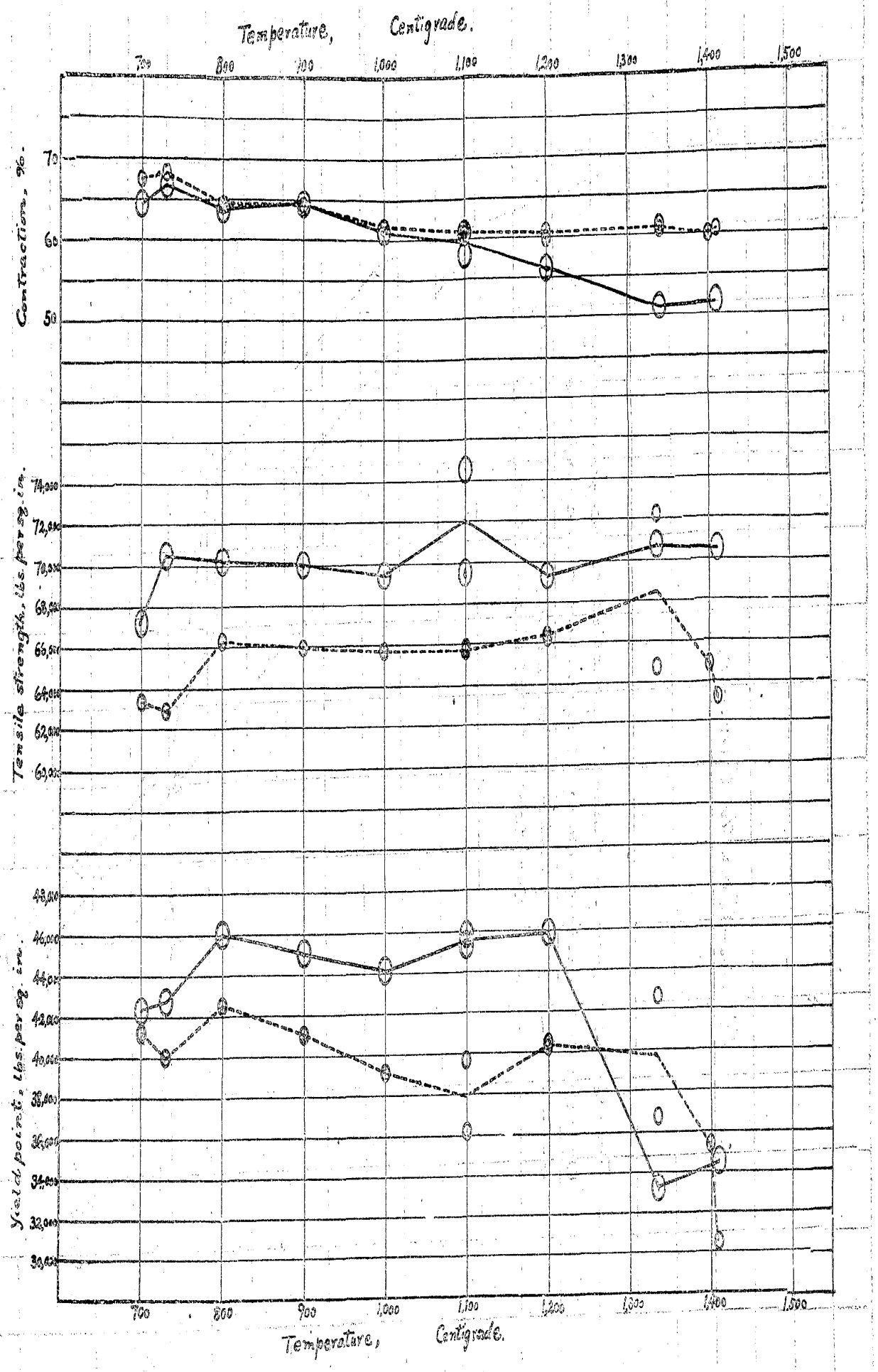

Fig. 45.—Curves of tenside strength, yield point and contraction due to varying temperatures.

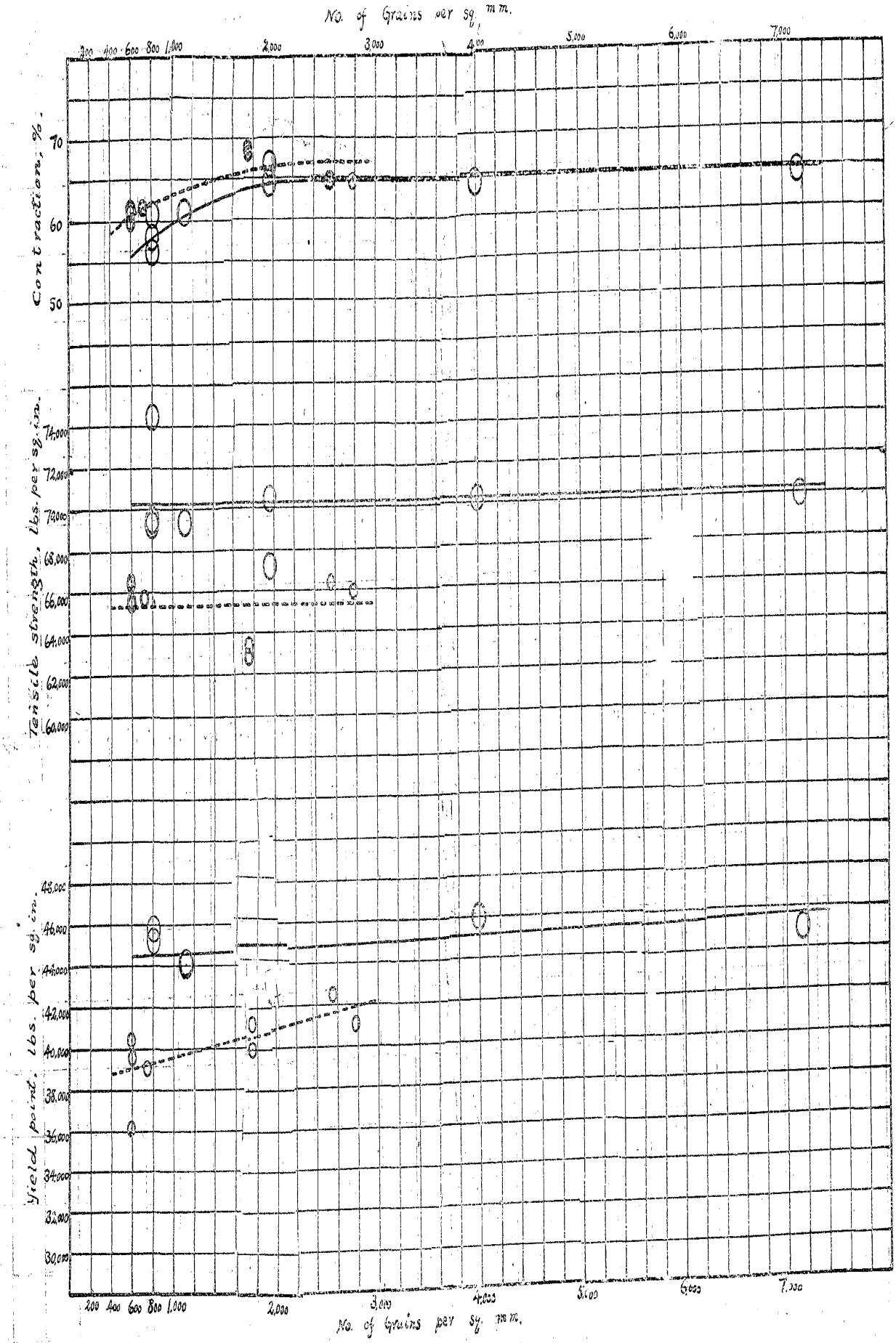

Fig. 46.—Curves of tensile strength, yield point and contraction due to different grain-sizes.

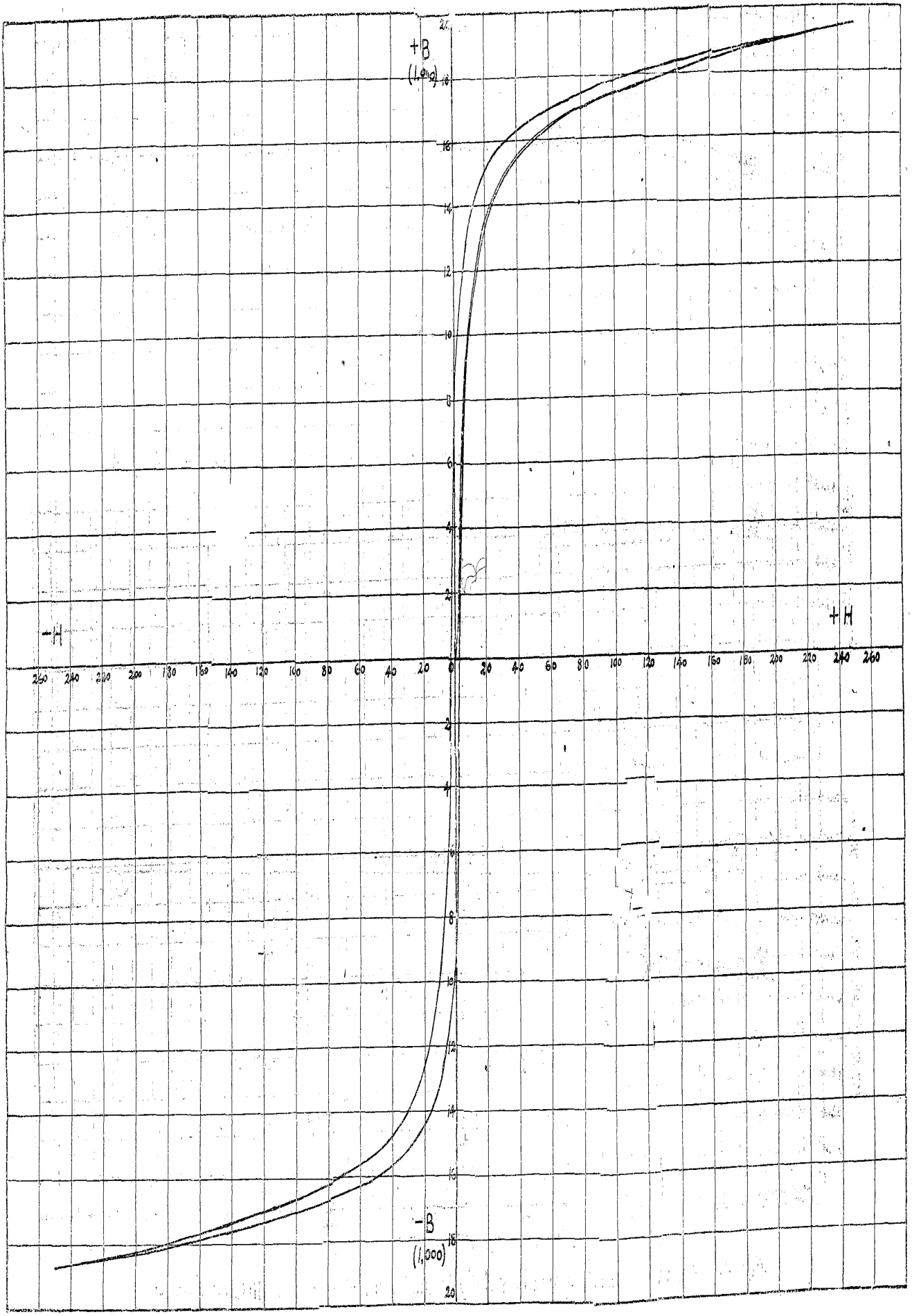

Fig. 47.—Hysteresis curve of the sample heated at 1100°C for one hour and cooled in the air.

GROUP A.—COOLED IN THE AIR. (FIG. 2.—FIG. 6.)

Heated up to Different Temperatures for One Hour.

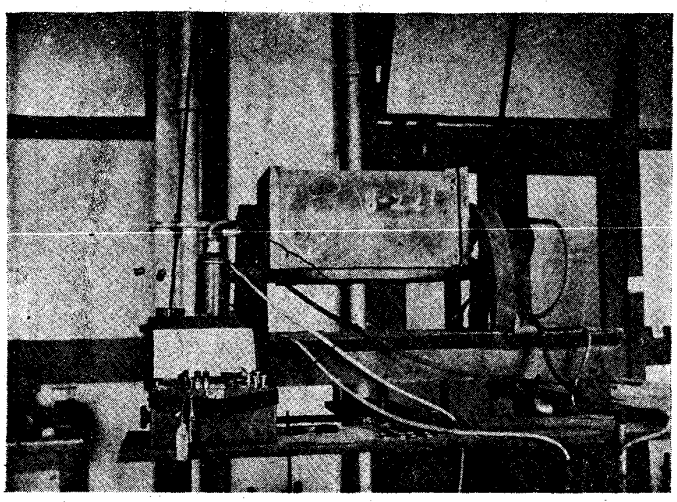

Fig 1.—Electric carbon tube furnace, and heat measuring apparatus.

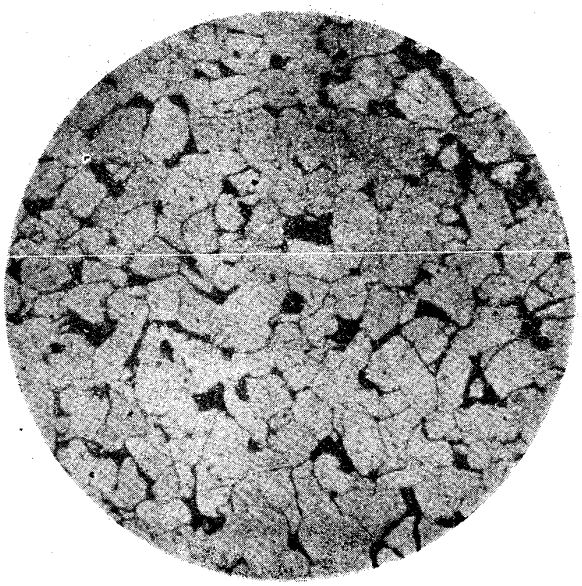

Fig. 2.—Original sample. ×200.

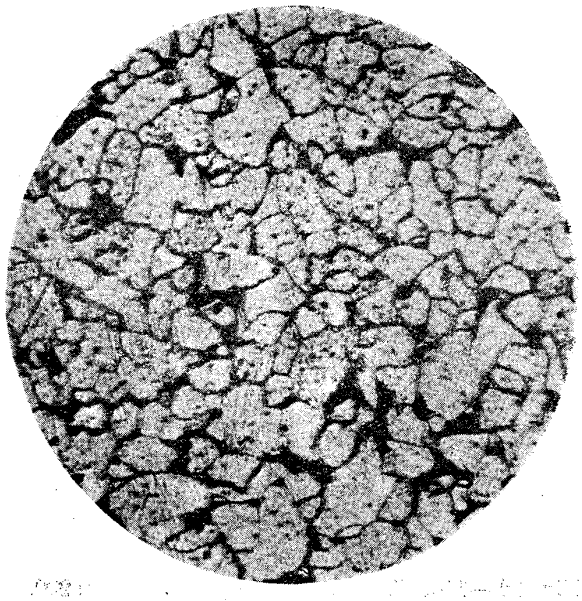

Fig. 3.—700°C. ×200.

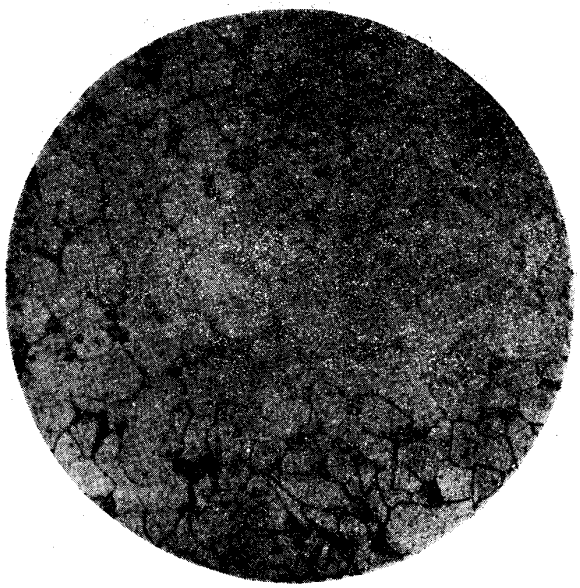

Fig. 4.—730°C. ×200.

Fig. 5.—800°C. ×200.

Fig. 6.—800°C. ×500.

GROUP A.—COOLED IN THE AIR.

Heated up to Different Temperatures for One Hour.

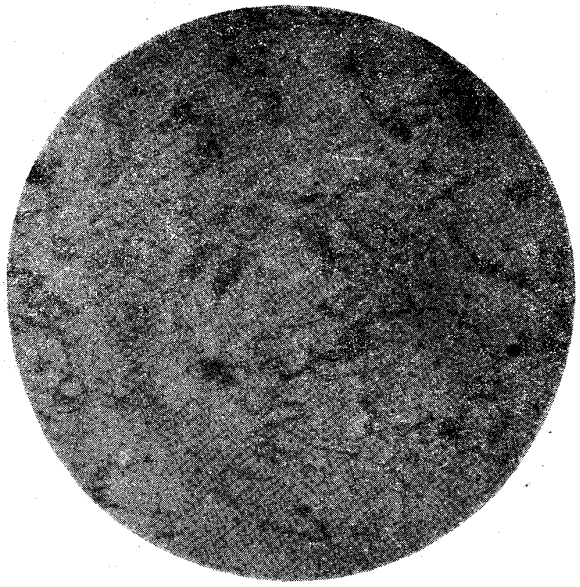

Fig. 7.—850°C. ×500.

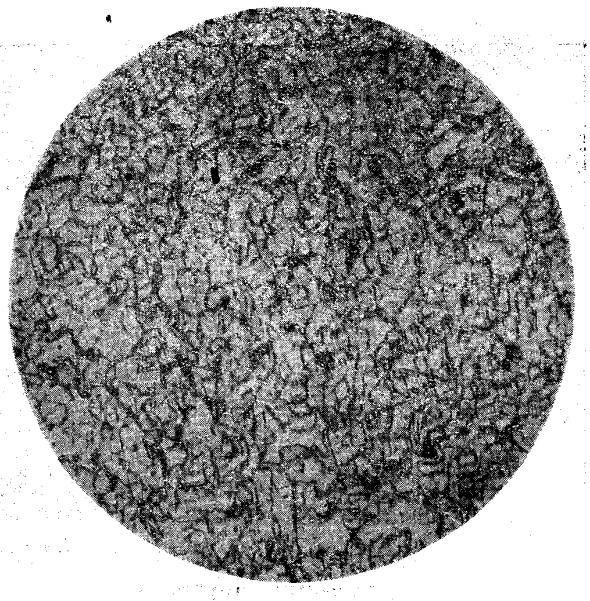

Fig. 8.—900°C. ×200.

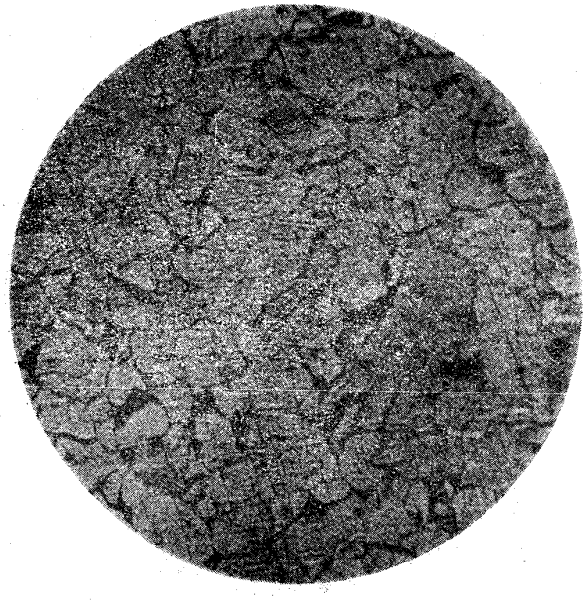

Fig. 9.—1000°C. ×200.

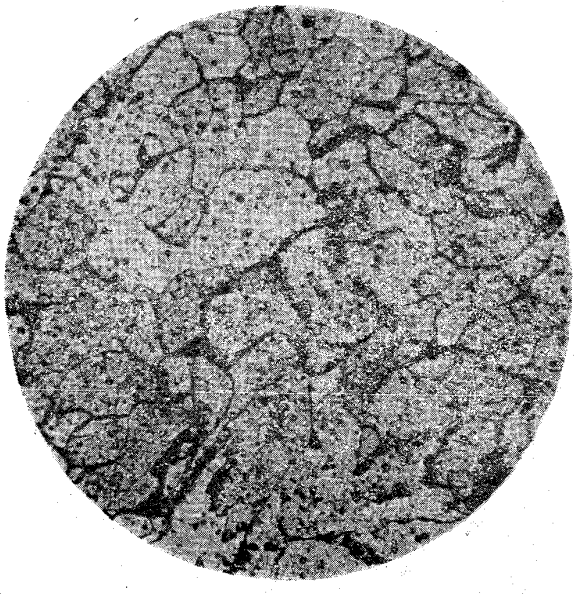

Fig. 10.—1100°C. ×200.

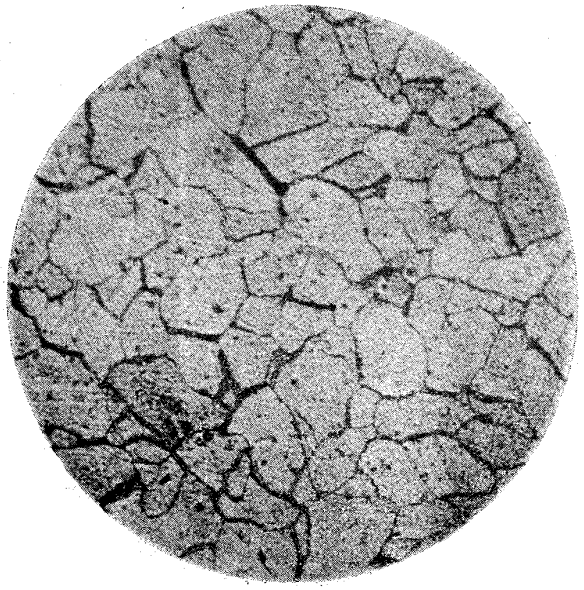

Fig. 11.—1200°C. ×200.

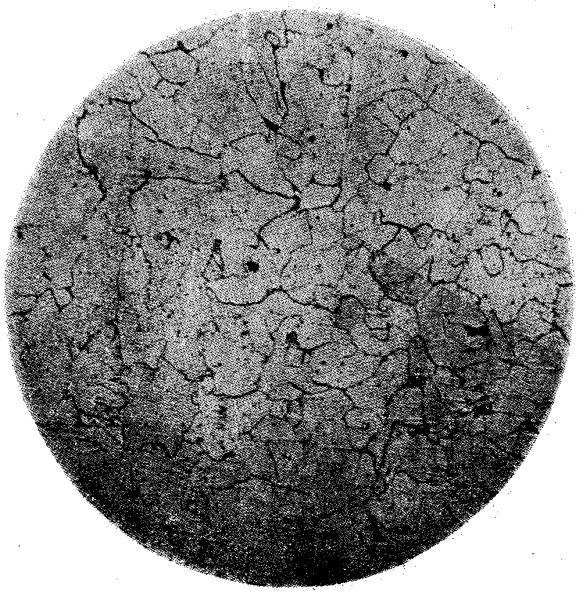

Fig. 12.—1335°C. ×100.

GROUP A.—COOLED IN THE AIR.

Heated up to Different Temperatures for One Hour.

Fig. 13.—1335°C. ×100.

Fig. 14.—1335°C. ×200.

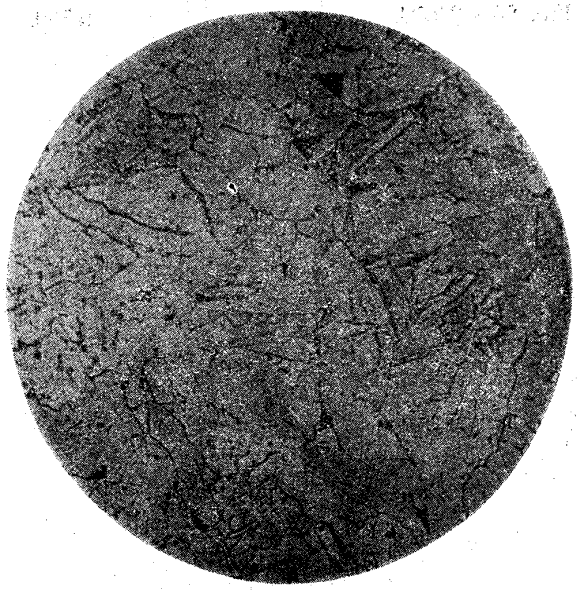

Fig. 15.—1410°C. ×100.

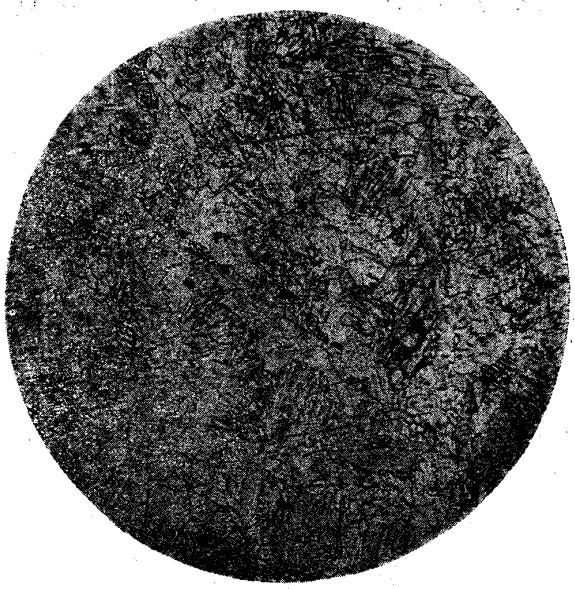

Fig. 16.—1410°C. ×40.

GROUP B.—COOLED IN THE FURNACE.

Heated up to Different Temperatures.

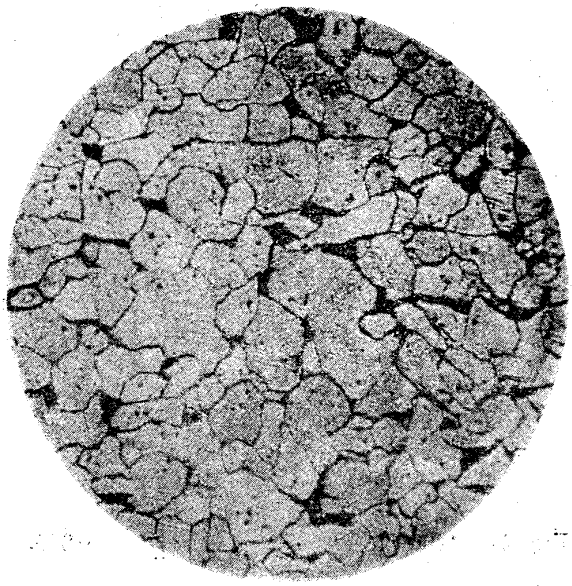

Fig. 17.—700°C. ×200.

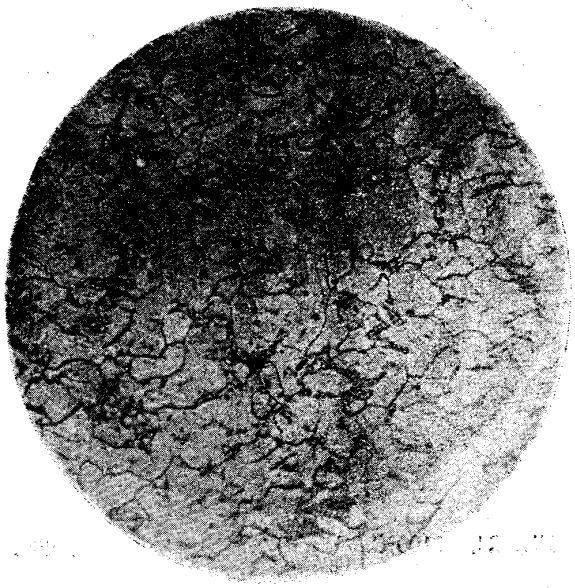

Fig. 18.—730°C. ×200.

GROUP B.—COOLED IN THE FURNACE.

Heated up to Different Temperatures.

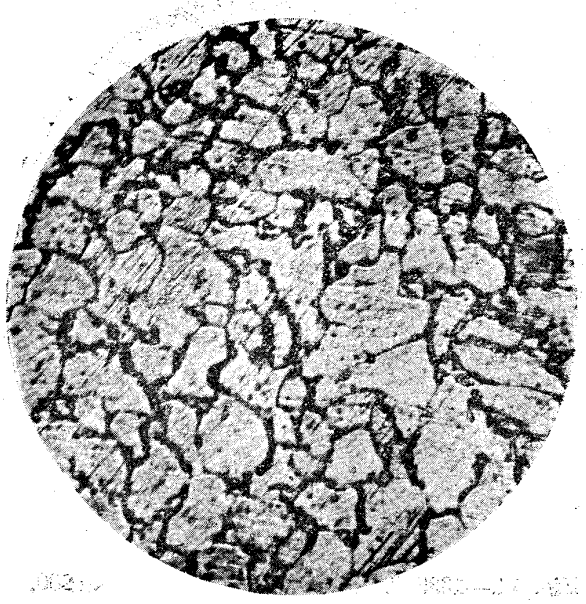

Fig. 19.—800°C. ×200.

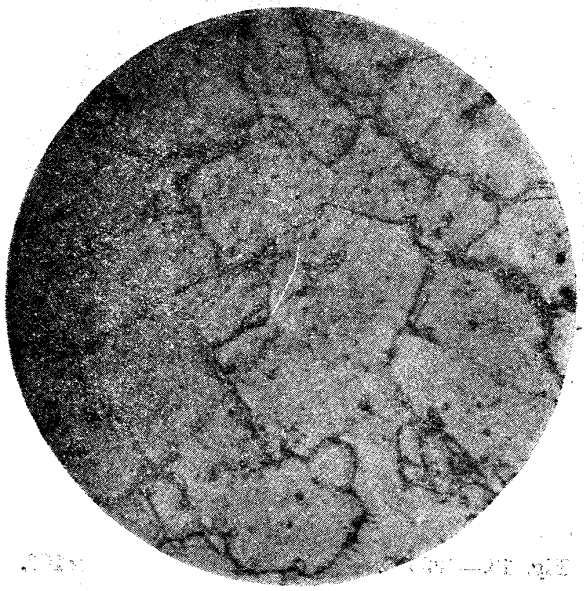

Fig. 20.—800°C. ×500.

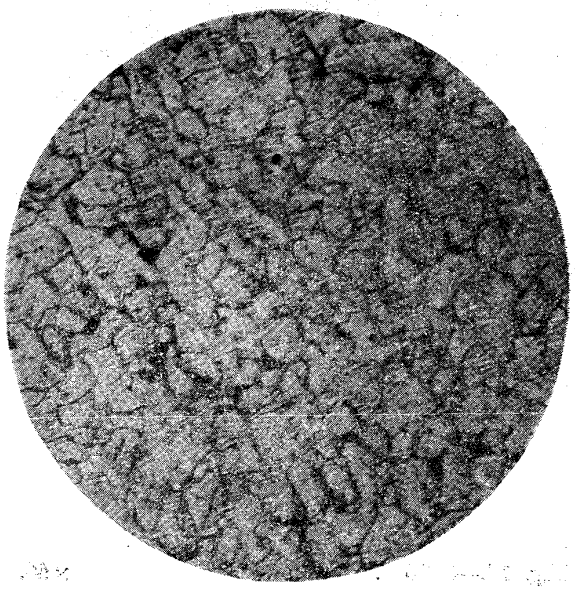

Fig. 21.—900°C. ×200.

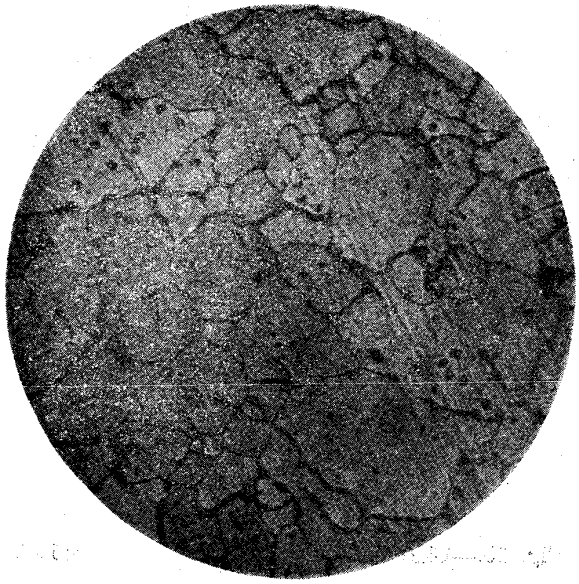

Fig. 22.—1000°C. ×200.

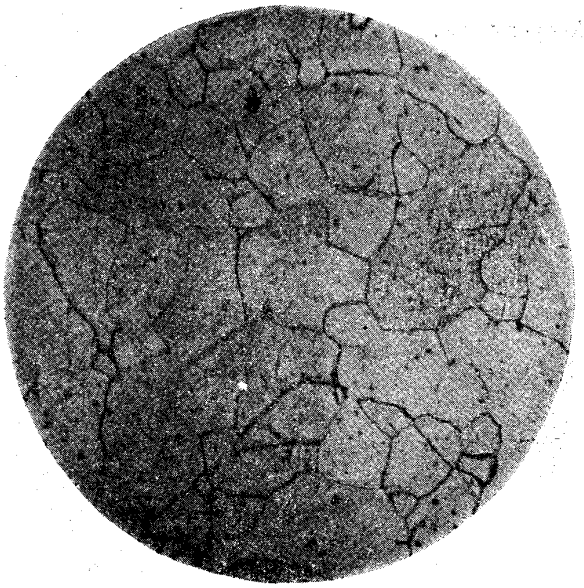

Fig. 23.—1100°C. ×200.

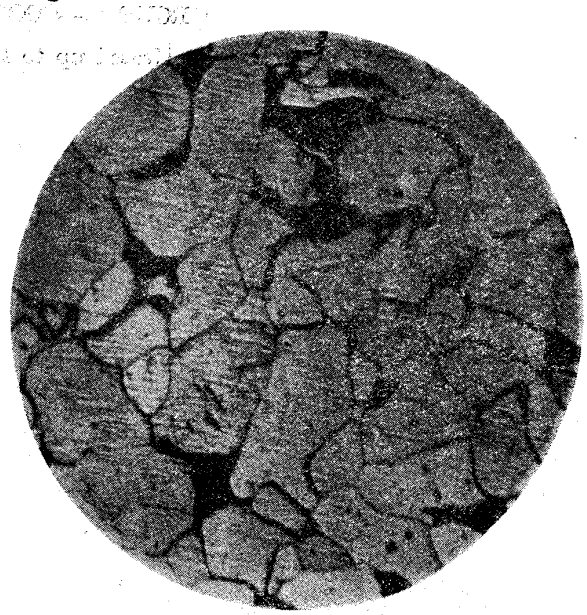

Fig. 24.—1200°C. ×200.

GROUP B.—COOLED IN THE FURNACE.

Heated up to Different Temperatures.

Fig. 25.—1335°C. ×100.

Fig. 26.—1410°C. × 40.

THE GRAIN-GROWTH DUE TO HEATING AT CONSTANT TEMPERATURE AND DIFFERENT PERIODS.

Temperature 950°C.

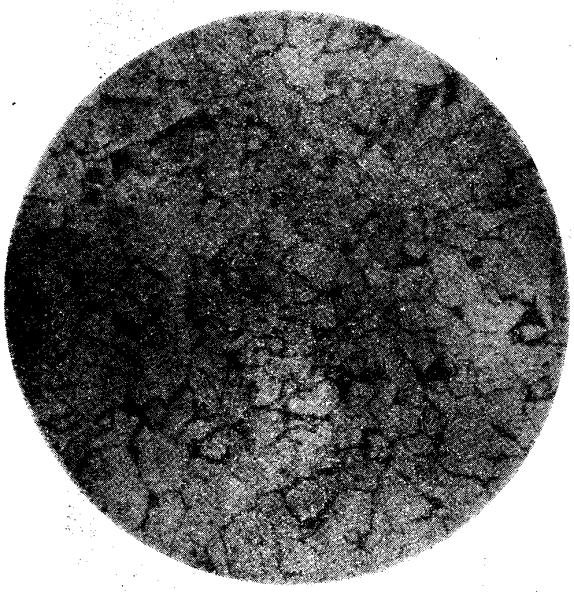

Fig. 27.—1 hour. ×200.

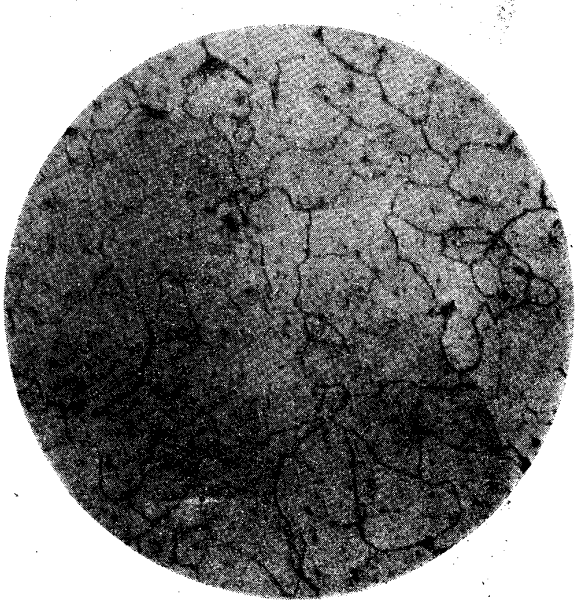

Fig. 28.—2 hours. ×200.

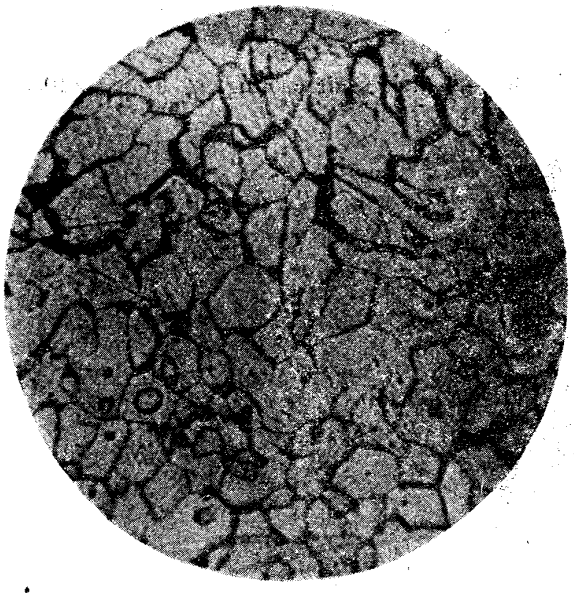

Fig. 29.—4 hours. ×200.

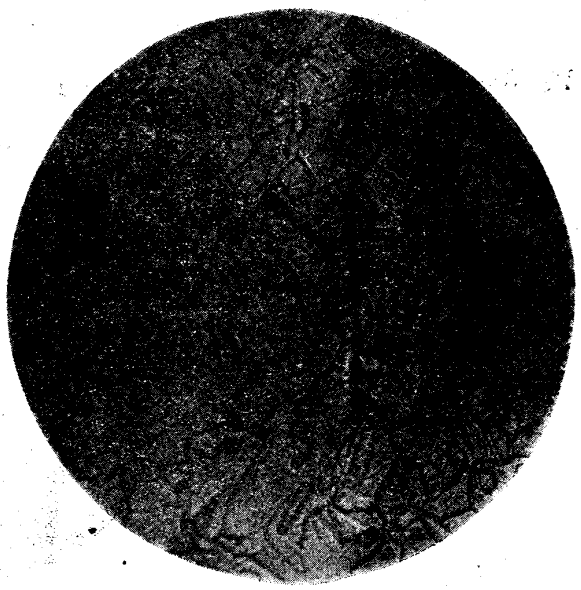

Fig. 30.—8 hours. ×200.

THE GRAIN-GROWTH DUE TO HEATING AT CONSTANT TEMPERATURE AND DIFFERENT PERIODS.

Temperature 950°C.

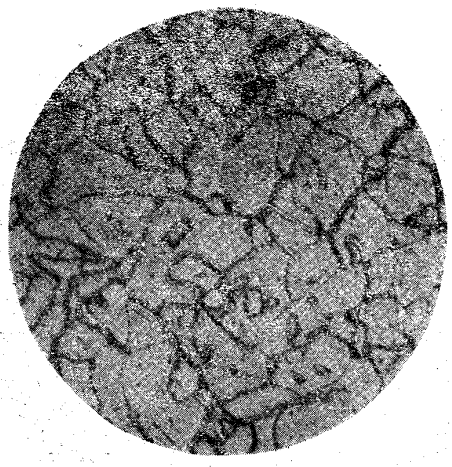

Fig. 31,—16 hours. ×200.

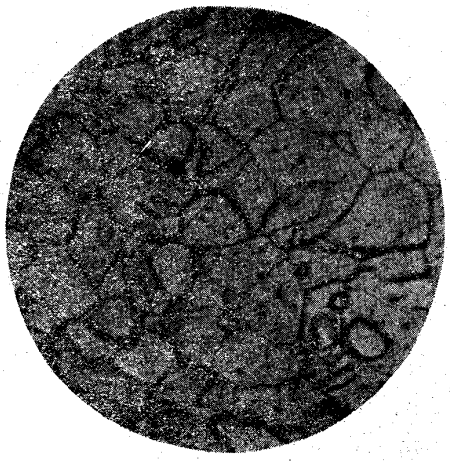

Fig. 32.—24 hours. ×200.

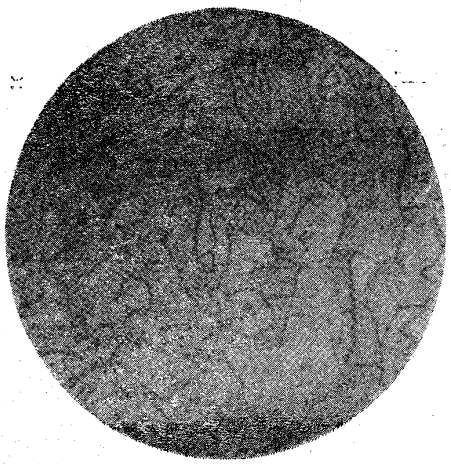

Fig. 33.—32 hours. ×200.

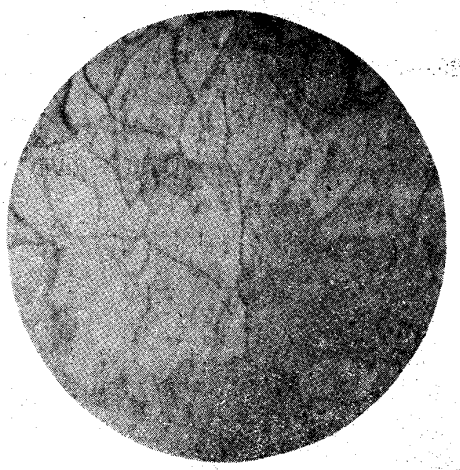

Fig. 34.—48 hours. ×200.

Fig. 35.—64 hours. ×200.

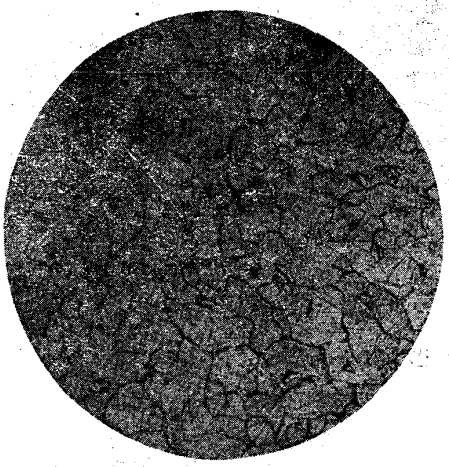

Fig. 36.—24 hours, air cooling. ×100.

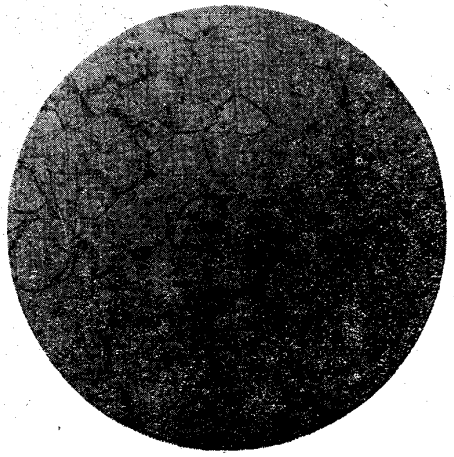

Fig. 37.—24 hours, furnace cooling. ×100.