A STUDY OF THE EFFECT OF HEAT TREATMENT ON THE DRAWING PROPERTIES OF STEEL WIRES

Respectfully submited to the Faculty of the Massachusetts Institute of Technology as a partial fulfillment for the Degree of Master of Science in Mechanical Engineering.

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HISTORY

Wire drawing was an old art. It was well known to the ancients without doubt, for we read in Exodus XXXIX.3, " And they did beat the gold into thin plates, and cut it into wires to work it in the blue, and the purple, and in the scarlet, and in the fine linen, with cunning work ", in making the sacerdotal dress of Aaron, the high priest of Israel and wire of similar fashion has been discovered dating back as far as 1700 B.C.

The wire produced then was far different from what is made now. In the olden days the metal was beaten into sheet metals and then cut into strips or threads. Not until the middle of the foerteenth century, the first wire mill was built by a German at Naremburg and the hand drawing has reached some degree Of excellence. From Germany it was extended to France and later on to England about 1565 when the people from other countries went there to dig the metallic ores and introduced the draw-plates.

In 1663 the first wire mill was erected in England, at Sheen, near Richmond, and from this date on; the mill maintains quite a strong footing and established a series of development.

Before there was such wire mill, iron rods of about ¼ of an inch square and 4 pOunds in weight were to be made at first and then drawn to the required size of wire, through draw-plates. This was done by means of a long pole which had a reciprocating motion, actuated by water power and in this way worked backwards and forwards. During the forward stroke it drew the rod and the wire through the plate. On its return stroke, the workman sat and coiled up the whole length ~~drawn~~ by hand into rings, and thus the process was continued until the rod was entirely drawn. The rods, however, were made of charcoal iron, because steel was not known yet.

The wires were then heated in a kiln to red hot and cooled. Scales thus formed on wires had to be remOved by hammering. Then they were scoured in a barrel, filled with gravel and water and rotated by water power for about 12 hours. When the wires were taken out, they were coated with flour lees and ready for further drawing. Pointing was either done by file or done in a smith's fire.

The old wire mill practice-In the

eighteenth century, when the rolling mill had its existence, a number of improvements were made to the wire manufacture. Insead of removing the oxide coating as previously described, it was done by putting the wire in a cistern which contains hydrochloric or dilute sulphuric acid. It was then cleaned with water and had all the traces and dirts removed. After having been thoroughly washed, it was coated with a mixture of lime and water and and put away until the lime was dried on. The pointing was usually done by mechanical means, or a pair of rotary hammers. The wire was finally handed to the drawer for further drawing , down to the required size.

Here the drawer was provided with a bench table on which was a tapered drum rotating on a vertical shaft driven by a pair of bevel gears underneath the table. The wire was pulled through a draft-plate ~~block~~ and wound on the drum. The draft plate had a number of tapered holes made by experienced smith, and finally finished and cold-punched to the required size by the wire drawer himself.

In making the rods, pig iorn, when in a molten state, was poured into a plate of about $2\frac{1}{2}$

inches thick. These iron plates were heated in a charcoal fire. These charcoal iron plates were cut into 4 inch squares, Or blooms, and, after passing eight or nine times the rolling mill, formed into bars of about 12 Or 14 feet long and $1\frac{1}{4}$ inches thick. These bars were again cut into lengths of about 2 feet each, and called billets which were then rolled about ten to twelve times and reduced into No.5 Or No.6 gage rod (0.212 or 0.192 inch in diameter). As the rods passed through the last pair of rollers, they were wound around a drum of about $2\frac{1}{2}$ feet diameter and now ready to be sent to the drawing mill. The cleaning process had to be applied before drawing, otherwise the draft plate wounld be ruined.

About 1860 when there was a great demand in galvanized fencing and telegraph wires, the wire business was later on led to two new inventions, namely, (1) the continuous galvaniging mill and (2) the continuous rolling mill. The next great improvement which revolutionized the entire trade is the introduction of the basic Bessemer steel, which is capable of rolling at lower heat and ~~and~~ gives wide range of steel wires from about 0.7% Carbon up.

Wire drawing was introduced as early as 1666 tO the United States. Until 1830 to 1860 no material development was made, except taht similar methods were adopted as in Europe. One of the first improvements was made in the Fall River Iron Works, where a rod mill was built. The original plant was destroyed by fire in 1839 but rebuilt in 1848.

Until 1860 the looping mill was unknown, the billets were passed through the rollers back and forth, The demand for longer lengths stir up the wire rod rollers, as the telegraphs and suspension bridge engineers were calling for materials with less welds and joints.

The Belgian type of rod rolling mill is a better type and sppeds up it s production to some extent. About 150 tons of No. 4 wire rods was produced in ten hours. It consists of a roughing-mill, which takes a 4 inch bloom, an inetrmediate mill, and a finishing train of rollers divided into two parts, the second half running at an accelerated speed to the first half. The large products have been possible bky the use of automatic reels placed at the dedivery end.

The mOdern process of wire drawing- A better appreciation of its importance is the reduction of ingots to wires. A 2-ton ingot, when roled and drawn to the average size of telegraph wires becomes elongated 20,000 times its original length. It invelves mainly the process of heat treatment, which may be classified as annealing, patenting, and hardening and tempering according to the carbon cobtent of the wire. The function of each of this heat-treatment will be discussed later. The practical application is surrounded in addition with many other technical considerations in which lie the art and the skill of the experienced wire drawer and wire mill man. In order to run properly, the rods must be prepared properly. The draw plate must have a proper tapered hole and length. The amount of reduction must suit the particular heat of wire. The speed must be also properly adjusted in order to suit the kind and the size of wire.

When the wire rods are finished, they are covered with a coating of iron oxide which is very brittle. If not removed, it would cause troubles to the die, as previously described. This is done away by the method, known as "pickling " process. The coils are first dipped into a dilute sulphuric acid bath of about 5% concentration for 5 to 10 minutes when the wire becomes silver grey, and then washed w with a stream of water at ~~about~~ a pressure of about

150 pounds. For some other purposes , the wires are covered with a rust coating under a fine spray of water and then dipped into a lime solution. During the acid bath, the wire is liable to absorbs a great amo-unt of hydrogen gas from the acid, causing acid brittleness. In order to prevent its danger, the wire-coils are then baked in a furnace at a temperature of about 400° F for from four to eight hours.

After the "pickling" process, the wires are carried to the drawing frame which consists of five or more blocks reducing from say No. 5 to about No. 14 gauge. After a wire has been drawn a certian number of drafts, it becomes so brittle that further drawing would break it. Therefore the heat treatment is to be applied on the wire. Annealing to allow carbon wire will relieve all strain set up by the cold work. For high or medium carbon steel wires , patenting is applied instead, because of the structure desired.

After the operation , the wire is again cleaned and washed and further drawn to the required size. Sometimes the drawings are dry and sometimes wet. In the dry drawing, powdered soap is used as a lunricant, which, in combination with the coating, forms a slippery surface between the die and the wire. In the wet drawing, the wire is is dipped into a coating solution of bluestone or copper sulphate. When it has taken a suffieient coating, it is put on a reel in a tube containing a solution of rye meal and subjected to the finishing drawing. The draft through the die produces a well-known color which is characterised as the "liquior" finished wire.

The Theory of Wire-drawing

In theory all that happens to a piece of wire in drawing is that its length is increased and its diameter is decreased by stretching. In the case of a soft wire, it is possible to reduce its diameter and increase its length by simply stretching it with its one end fixed and pulling at the other. In that kind of stretching, however, we do not have any increase in its tensile strength, as there is no such circumferencial compression as is produced in drawing a wire through a die.

The problem of wire-drawing is really one of flow of metal through a reducing orifice and mathematical formulas for total pulling force P and total circumferencial pressure R exerted on the walls of the die may be deduced on this assumption. In order to ~~take~~ get some general idea of the magnitude of P andR, let us take, as an illustration, the case of drawing a No. 5 gauge rod of .10% C. steel to No. 8 gauge. In this case, P is equal to 1500lb. while the circumferencial pressure R on the shoulder of the die equals ~~to~~ 63 tons per sq. in. of curved surface.

In considering the problem, a unit volume of

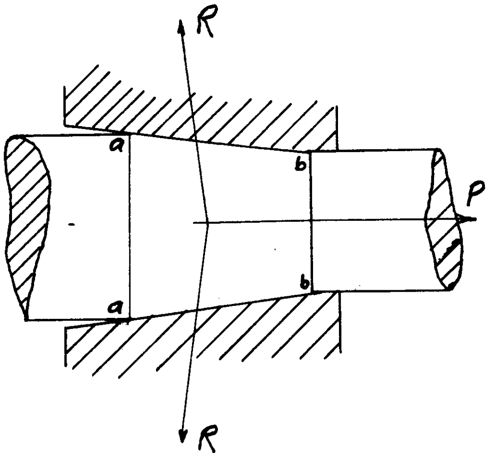

Fig. 1.

material is taken, represented bythe truncated cone aa, bb, in Fig. 1. The actual work done by P in drawing the wire through the die equals 35.9 ft.-lb. *Theoretically, a total of 24.6 ft.-lb. only is required to effect the reduction of the unit volume; 15 ft.-lb. being expended in compression and 9.6 ft.-lb. in stretching. Therefore, the work lost in overcoming friction amounts to 11.2 ft.-lb., or 31.3% of the total. The total pull may with safety be allowed to amount to 75% of the breaking strength.

With the enormous pressure of 63 tons per sq. in., it is evident that some form of lubricant should be used. A large part of the success in drawing depends upon use of proper lubricants.

For the correct drawing of wire, it is absolutely necessary that the metal should pass through the draw-plate with even lines of flow. For instance, all the points in a plane section ~~ea~~ 1-1 should still remain in a plane section after passing through the die, such as ~~ob~~ 2-2, + 3-3 in Fig. 2. If the core lags behind, as shown in Fig. 3, or if the skin lags behind, as shown in Fig. 4, the wire will ~~not~~ be spoiled. The commonest defect comes

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*"Steel Wire and WIRE DRawing",Trans.Liverpool Eng.Soc. Feb.,1920.

under the second case, giving the well-known phenomena of "cuppiness" in wire, which means that the core is actually fractured, before any sign of failure is visible on the skin, and which, of course, causes extreme brittleness. Any defect in steel or in method of manufacturing which causes uneven flow of metal through the die will cause "cuppiness", a common case being that due to a hard core of segregated high carbon content.

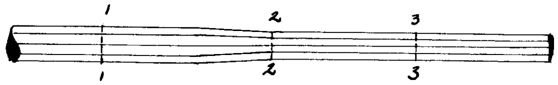


Fig. 2

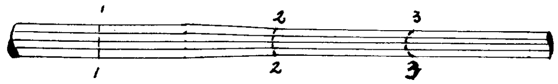


Fig.3

Fig. 4

The critical part of a wire-drawing machine is ~~h~~the die and upon its proper design and maintenence hte success of the draw depends. By improving the shape of the die hole, we may often save a great deal of power. Unfortunately, there are no set rules for its design, though the laws of flow through a reducing orifice is well-established. Thus, one manufacturer will say that the reduction of the area of the wire in drawing by 1/5 is the best, while another will claim an elongation of 50% in one pass. The truth seems to be that the shape also depends upon whether hard or soft steel is to be drawn.

In England, dies are generally made of steel, although cast iron is sometimes used in drawing copper, and diamond dies are employed in drawing long lengths of fine wires in continuous machines. But in America, chilled cast iron plates are very often used for the heavier sizes of wire..For the heavy work of "breaking down", the die plate has usually from a dozen to 18 holes, which are of the same size and used in turn, as they wear out.

Up to the last ten years, the drawplates were all made of simple carbon steel containing about 1.6% C., but now very hard dies have been used containing up to as much as 13% of chromium. These dies give good results in practice, the wearing being very slow~~ly~~, if at all. But some wire-drawers prefer the old type pf dies for certain kind of work, for the die hole will give a little, and the wire will not draw so "harshly".

The proper shape of hte hole for a "breaking down" die is shown in Fig. 5. It has two distinct zones, a comparatively short tapered section, in which the actual drawing is done, and a bell mouth leading up to it. The

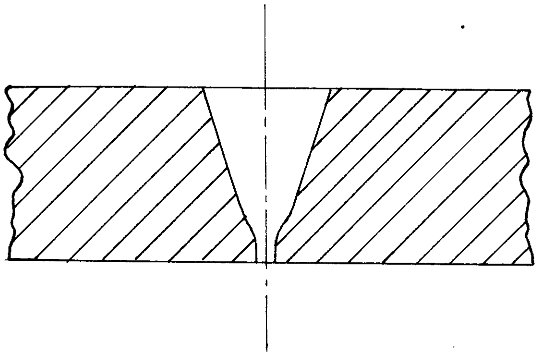


Fig. 5

important point is that the bell mouth should have a well-rounded approach to the taper, so that its walls are quite clear of the entering wire. Without this precaution, there is a liability for the metal of the die to be drawn forward by the wire, and piled up in the throat, the hole being "pulled out". Thus, the opening becomes too small and the wire is scrapped. The same effect may be produced, if the wire is not thoroughly lubricated.

The reason for the peculiar shape of the die hole may be found in the material used ~~in~~ for the die, namely, plain carbon steel containing 1.5 to 2% C., and the method of hardening it. Owing to the impossibility of maintaining the size of the hole in heat-treatment, the metal around the hole is hardened by hammering, called "battering". This work-hardening can obviously be made to penetrate only a limited distance below the surface of the die, and this is the reason why the bell mouth must be cleared well back from the bearing part of the hole, which is of a depth corresponding to the thickness of the hardened metal. After hardening, the hole is brought to exect size by means of a punch, which further hardens the metal~~s~~ around the hole.

Diamond dies consist~~s~~ of commercial diamonds drilled and mounted in brass or other metal cases. ~~The~~ Its great superiority over the other dies is due to the hardness of diamond, and its freedom from wear,which enables large quantities of wire of uniform size to be produced without changing the die. In the manufacture of these dies, the diamonds are first trimmed with diamond poi~~o~~nts and ~~are~~ ~~then~~ ~~and~~ are then drilled with small steel drills, fed with diamond powder, and made to oscillate for many hours. The holes are finally polished to the required gauge within one-ten-thousandth of an inch.

The speed at which the wire passes through the die depends upon the hardness of the wire and its diameter. The most economical speed for a particular kind of wire has to be determined experimentally.

*Formulas Showing Approximately the Relation between Quantities Involved in Wire-drawlng.

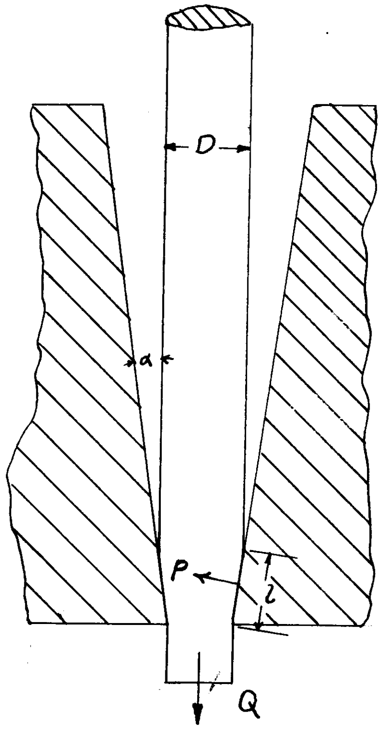


Fig. 1.

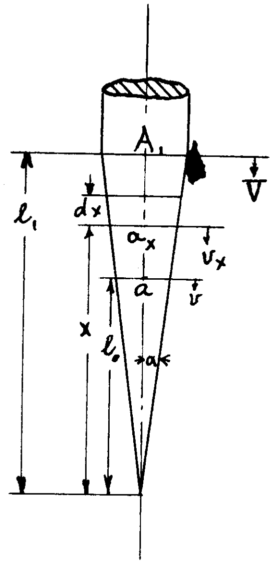


Fig.2

V = Velosity of wire before entering the die.

D = Diameter of wire before entering the die.

A_1 = Sectional area ofwire before entering the die.

v = Velosity of wire after leaving the die.

d = Diameter of wire after leaving the die.

a = Sectional area of the wire after leaving the die

v_x = Velocity of a section of wire inside of the die.

d_x = Diameter of this section.

a_x = Area of this section.

*Trans. Am. Inst. Mining Eng. Page 672, Vol. IX, 1881.

Δ = An element of the tapered surface in contact with the wire.

p = Mean pressure per sq. in. on the tapered surface.

P = Total pressure on the tapered surface.

l = Length of taper of wire in the die, = (nearly) length of center line.

Q = Total force acting on the wire in direction of motion.

α = Angle between the tapered surface and center line of wire.

V_m = Mean velosity of the whole rod in passing through the die.

f = Coefficient of friction in the die.

Assuming the same ~~velo~~ density for different parts of the rod, we have

$$VA_1 = v_x a_x = va \qquad (1)$$

Calling V_m the mean velocity of the whole rod, we obtain from Fig. 2,

$$V_m = \int_{l_0}^{l_1} \frac{v_x\,dx}{l_1 - l_0} \qquad (2)$$

From eq.(1), we have

$$v_x = \frac{VA}{a_x}$$

and by substituting this value of v_x in eq. (2), we obtain

$$V_m = \frac{VA}{l_1 - l_0}\int_{l_0}^{l_1} \frac{dx}{a_x}$$

We have from Fig. 2 also,

$$\frac{a_x}{A} = \frac{x^2}{l_1^2}, \qquad a_x = \frac{Ax^2}{l_1^2} \tag{4}$$

Substituting in eq. (3),

$$V_m = \frac{V_1 l_1^2}{l_1 - l_0}\int_{l_0}^{l_1}\frac{dx}{x^2} = \frac{V l_1^2}{l_1 - l_0}\left\{\frac{1}{l_0} - \frac{1}{l_1}\right\}$$

or,

$$V_m = V\frac{l_1}{l_0} \tag{5}$$

From Fig. (2), also

$$\frac{l_1}{l_0} = \frac{D}{d} \tag{6}$$

and by substituting in (5),

$$V_m = V\frac{D}{d} \tag{7}$$

Taking the work done ih consideration, we obtain from Fig. (1),

$$P(\sin\alpha + f\cos\alpha)\, V_m = Qv \tag{8}$$

And by substituting in this the value V_m as found in eq. (7), we have

$$P(\sin\alpha + f\cos\alpha) V\frac{D}{d} = Qv$$

By substituting the of v as found in eq. (1), we have

$$P(\sin\alpha + f\cos\alpha)\frac{D}{d} = \frac{QA}{a}$$

But

$$\frac{A}{a} = \frac{D^2}{d^2}$$

Hence,

$$P(\sin\alpha + f\cos\alpha) = \frac{QD}{d} \qquad (9)$$

From Fig. (1),

$$\sin\alpha = \frac{D-d}{2l}$$

Therefore,

$$\cos\alpha = \left[1 - \left(\frac{D-d}{2l}\right)^2\right]^{\frac{1}{2}}$$

Hence,

$$P = \frac{QD}{d\left\{\frac{D-d}{2l} + f\sqrt{1-\left(\frac{D-d}{2l}\right)^2}\right\}} \qquad (12)$$

Effects of wire-drawing on the Physical Properties and Constituents of Steel.

The general effects of wire-drawing on the tensile strength ~~and~~, elongation, and torsion of plain carbon steel are ~~to~~, more or less, familiar to all. But comparatively few know the effects on the density of the wire. When apiece of wire is drawn through a die, its density increases at first due to the compression exerted by the walls of the die. But after the reduction has reached a certain stage, if the wire is subjected to further drawing, it will actually gets lighter and is over-drawn. At that critical stage, the tensile strength will begin to increase very rapidly, but the wire becomes exceedingly brittle, as shown by its low torsion and elongation. The wire is ruined and not good for any practical purpose.

The effect of drawing on the hardness of the sorbite is interesting. When the cold work is not carried beyond a critical point, where the grains of sorbite and pearlite are broken up into fibers and lose their identity, it does not result in hardening the grains to any appreciable amount. This is, probably, due to the formation of slip bands, so that although the crystals in individual grains slide over each other, and the polyhedric grains are made over into long fibers, the physical properties are not damaged (save the elongation), but on account of the increase in density, are actually benefited thereby.

But if the cold work is carried to a stage where the particles of one grain are moved till they encroach upon and penetrate into other adjacent grains, and perhaps till the whole grain be actually torn apart, so that the entire structure is made of fibers more or less torn apart, then the hardness seems to increase and also brittleness. This extremely brittle wire is not of much use.

If this wire-drawing be carried still farther, even the tensile strength will decrease. The increase in ultimate strength due to a tensile stress is explained by Rosenhain as due to the formation of new slip bands in grains whose crystals are not oriented in a direction as favorable for slipping as when the stress is first applied.

The reason for increase in hardness after a certain critical stage may be due to an [*]allotropic change

[*] Jl. Iron and Steel Inst.-page 139, No.2, 1908.

in the iron, or to a chamical change in the carbon, or both.

It may be of interest to mention that grains Of pure ferrite do not increase in hardness under the heaviest deformation obtained in wire-drawing. There is , of course, a hardening effect given to the whole wire, but this lack of ductility seems to be due to the fact that no more slipping over each other of the crystals can take place, but the actual grains themselves do not seem to be hardened.

Pure iron, thougn softer than steel, would not stand as much drawing as the steel of sorbitic-pearlitic structure. This fact is probably due to the tenacity of iron being much less than that of a eutectoid steel. The iron wire draws nicely for three or four holes, but by that time all the slip-bands that can be formed have already slid, and the metal has to break, since it can yield no longer. In the steels of sorbitic-pearlitic structure, the ferrite is strengthened immensely by the cementite, and since both the ferrite and pearlite, as present in a soft steel, undergo a mutual deformation when subjected to stress, it follows that in a number of holes of wire-drawing the steel elongates gradually, while the iron has its "stretch" nearly all removed by the first two or three holes, so that in the finished wire, elongation is less than the steel wire.

Deteriorating Effect of" Acid Pickle" on Steel Rods.

Experiments to determine the effects of " acid pickle" on steel rods and wires have been conducted by many investigators. One good procedure is as follows:-

(a) Take samples in the following stages:

(1) Before pickling. (2) After acid pickling.
(3) After"rusting". (4) After lime coating.
(5) After baking.

(b) Test each sample for tensile strength, elongation, torsion, and reduction of area. The test of reduction of area is a very important one,for it shows the effects of pickling much better than the other physical tests. When a sample is properly pickled, a specimen from the 5th stage always shows a definite "necking in" characteristic on fracture by tensile test.

"Acid brittleness" is fatal to wire,and all effects of acid pickling should be carefully removed. The brittleness is due not so much to the acid being not removed, as to the hydrogen absorbed by the wire when in the a-cid bath. The use of long furnaces is very effective in drawing out the absorbed hydrogen by long heating.

The Heat-treatments of Wires/Steel.

The principal heat-treatments used in wire manufacturing are: (1) annealing; (2) patenting; (3) hardening and tempering.

I. Annealing.

Annealing in wire manufacturing serves to accomplish three functions:- (1) To remove the effects of hardening due to cold work in wire-drawing. Annealing for this purpose covers principally the low carbon steel wires, those with .25% C. or under. Some authorities seem to recognize the fact that in such annealing, it is not absolutely necessary to reach the critical temperature. (2) To refine the grains- applied principally to the higher carbon wire, those with .30% C. or over. (3) To obtain some definite structure, i.e., spheroidized cementite. This treatment is used for wires serving special purposes.

Effect of initial annealing.- Authorities have divergent opinions on the neccessity of initial annealing. Mr. J. Dixon Brunton's conclusion* is that annealing the rod before the final annealing does not in any way produce better material and is, therefore,

*P.143, No.2.,1906. Jl. Iron and Steel Inst.

not necessary. But Mr. Longmuir maintained that annealing before drawing is necessary to insure uniformity inthe final wire.

The actual increase in elongation after annealing depends upon the time the metal is under treatment, but at end of five minutes(usually), the maximum increase in elongation at any temperature has reached. This simply means that the material has been thoroughly heated by that time and the effect of cold work has all been removed.

Reducing the wire too much before annealing causes "crystallization" and the wire continues to be brittle after annealing.

II. Patenting.

Patenting is a term used in wire-drawing industry to describe a process which aims at leaving ~~the leaving~~ the material at sorbitic state. It is usually for medium carbon steel (.35% - .85%), when both strength and toughness are required. It would be impossible to make rope and music wires without patenting. The process consists of heating above the critical range and cooled fairly rapidly, (such as in air), through the critical range. The high tensile strength is due to carbon in solution, while toughness is due to its fine grain structure. The functions of patenting are: (1) in the process of manufacture, the removal of cold work, and (2) in the finished wire, to give together with cold work, desired strength and toughness. Patenting permits more cold work than annealing, which is due to its toughness.

III. Hardening and Tempering.-

Hardening and tempering apply to the higher carbon steel wire, from .65%-1.00% , In wire-drawing, they are considered as one continuous process, there being no field of usefulness for wire simply hardened. The wires are drawn through heated tubes of furnace, quenched in oil or water, and, finally, tempered in a bath of molten lead in one process.

Procedure

After a carefull study, it has been decided that the low carbon steel wire-stock is to be annealed and the medium carbon steel wire is to be annealed and patented respectively. After the heat-treatment, the wire is "pickled". Mark "A" is assigned to the low carbon wire annealed and "B" and "C" to the mediuem carbon annealed and patented wires. The wire is then tested for its tensile strength and torsion. It is drawn and reduced through about ten drafts from .111" diameter to .036" diameter for the annealed stock and to .029" for the patented stock. Tests for its physical properties are carried out for each, or every other draft. The specimens "A", "B" and "C" are each subscripted with 1, 2, and so on indicating the number of draft it has been passed through.

The same procedure is conducted for the intermediate heat-treatments, on A, B, and C. For instance, AX_0 is annealed after the 10 tenth draft pickled, tested and drawn further down to AX_1 which is again tested and further drawn. to AX_2 and so on down either to the limit of the die hole or till the specimen breaks.

Specimens A and B are annealed at about 16oo° F and 1480° F respectively in a gas furnace Specimens C are patenetd by feeding very slowly through a tubular electric furnace heated to about 1480° t0 1500° F. The feeding speed is kept very slow so as to have the wire patented thoroughly.

The scales formed after the heat-treatment are removed by the pickling process. The wire is first uncoiled and coiled up again so as to loosen ~~up~~ them up and then put into an acid bath which is made of about 5% concentrated sulphuric acid at 160° F for 5 to 10 minutes. Then it is washed with water and subjected to a fine spray of water at a slight pressure. until a dark-green and brown coatinq is formed. It is next dipped into a boiling lime solution and quickly removed and finally dried in an oven at about 250° F for 4 hours.

A 100 diameter gage is adopted for the torsion test and 25" gage length for the tension test. The twisting numbers and the load and the elongation are thereby recorded for each test.

In drawing the wire is first pointed by file and then pulled though the die about 30" long so as to be capable of winding upon the drum which is about 4½" in diameter and tapered to about 4¼" in diameter and is at distance of about 10" between the center of the drum and the die block. Such a small drum is, with no particular reason, but simply becaues of the limited stock in hand. It would be very much better if the drum is made larger. The drawing frame consists of nothing but a small D.C. motor a pair of reduction gears, and the drum. The speed reduction is about ~~about~~ 30 to 1 ratio. The drawing speed then is about 7" per second, which is very slow indeed. Owing to the size of the drum, the springing action of the wire sometimes causes entanglement. The amount of reduction for the smaller wires is a little hea-vier than that for the larger.

Being lack of die supply, jewelers' dfaft-plates were bought from the market. These draft-plates imported from France, are made of very low carbon steel. For the soft stock and light reductions, they will serve the purpose alright, but they can never stand the medium carbon steel stock at all. These draft-plates are, therefore, case hardened and quenched in oil, at about 1600° F. Furthermore, the holes are not made to the standard gages at all.

Wire Stock Composition

Mark	A	B	C
C %	.10	.45	.45
Mn %	.35	.88	.88
S %	.050	.045	.045
P %	.023	.017	.017
Si %	....	.14	.14

·45 % C. Steel Wire, Annealed.

Specimen No.	Wire		% Reduction		Maximum Load. Lbs.	Tensile Strength Lbs./□"	Elongation in 25"		Torsion in 100 Diam.
	Dia. Inches	Area Sq. Inch.	Overall	Successive			Inches	%	
B_0	0·111	·009677	0	0	884	91,400	3·20	12·8	49·5
B_1	0·107	·009020	6·78	6·78	905	100,000	0·935	4·28	53·5
B_2	0·095	·007088	26·8	21·4	—	—	—	—	—
B_3	0·085	·005674	41·3	19·9	740	130,000	0·35	1·40	45·0
B_4	0·078	·004778	50·6	15·8	—	—	—	—	—
B_5	0·070	·003848	60·3	19·4	—	—	—	—	—
B_6	0·069	·003139	61·4	2·83	573	153,000	0·37	1·48	38·0
B_7	0·058	·002642	72·7	29·4	—	—	—	—	—
B_8	0·052	·002124	78·2	19·6	—	—	—	—	—
B_9	0·046	·001662	82·6	21·8	296	178,000	0·27	1·08	35·0
B_{10}	0·038	·001134	88·2		Failed, when part way through.				
B_{11}									

·45 % C. Steel Wire, Annealed.

Specimen No.	Wire		% Reduction			Maximum Load. Lbs.	Tensile Strength. Lbs./□"	Elongation in 25"		Torsion in 100 Diam.
	Diameter Inches	Area Sq. Inch.	Over-all	After Intermediate Annealing	Successive			Inches	%	
	Annealed Again After B_9									
$B\mathrm{X}_0$	·0452	·001605	83·4	0	0	144·5	90,000	2·50	10·0	$42\frac{1}{2}$
$B\mathrm{X}_1$	·0393	·001213	87·2	24·4	24·4	144·8	119,000	0·10ˣ	0·4ˣ	37
$B\mathrm{X}_2$	·0323	·0008194	91·7	55·2	32·2	115·0	140,300	0·16	0·64	$33\frac{1}{2}$
$B\mathrm{X}_3$	·0267	·0005599	94·1	65·2	31·7	87·5	156,200	0·12	0·48	35
$B\mathrm{X}_4$	·0220	·0003801	96·0	76·4	32·1	62·5	164,200	0·04	0·16	22
$B\mathrm{X}_5$	·0210	·0003464	96·4	78·5	8·87	60·0	173,200	—	—	$22\frac{1}{2}$
	Annealed Again After B_8									
$B\mathrm{VIII}_0$	·0489	·001878	80·5	0	0	171	91,200	2·58	10·3	$45\frac{1}{2}$
$B\mathrm{VIII}_1$	·0474	·001765	81·7	6·02	6·02	[illegible]	—	—	—	—
$B\mathrm{VIII}_2$	·0410	·001320	86·4	29·7	25·2	159	120,000	0·15	0·60	39
$B\mathrm{VIII}_3$	·0323	·0008194	91·6	56·5	31·9	117	143,000	0·12ˣ	0·48ˣ	$37\frac{1}{2}$
$B\mathrm{VIII}_4$	·0271	·0005768	94·0	69·2	29·6	89·5	155,000	0·12ˣ	0·48ˣ	$32\frac{1}{2}$
$B\mathrm{VIII}_5$	·0221	·0003836	96·1	79·6	33·5	65·2	169,500	0·19	0·76	$36\frac{1}{2}$
$B\mathrm{VIII}_6$	·0219	·0003767	96·2	80·0	1·8	63·0	167,100	0·10ˣ	0·40ˣ	$27\frac{1}{2}$

Note: × denotes "Beyond gage".

·45 % C. Steel Wire, Annealed.

Specimen No.	Wire		% Reduction			Maximum Load. Lbs.	Tensile Strength. Lbs/□"	Elongation in 25"		Torsion in 100 Diam.
	Diameter Inches	Area. Sq. Inch.	Over-all	After Intermediate Annealing	Successive			Inches	%	
Annealed Again After B_7										
B VII$_0$	0·0578	·002624	72·9	0	0	231·5	88,500	3·47	13·9	41
B VII$_1$	0·0500	·001964	79·7	25·1	25·1	227·0	115,500	0·28	1·12	45·5
B VII$_2$	0·0472	·001750	81·9	33·3	10·9	217·0	124,000	0·40	1·60	50
B VII$_3$	0·0410	·001320	86·4	49·7	24·5	177·0	134,000	0·22	0·88	39
B VII$_4$	0·0323	·0008194	91·5	68·7	37·9	126·0	153,700	0·10^{x}	0·40^{x}	35½
B VII$_5$	0·0272	·0005810	94·0	77·8	29·1	92·5	159,200	0·08^{x}	0·32^{x}	37
B VII$_6$	0·0218	·0003732	96·2	86·0	35·8	Failed, when part way through.				34
Annealed Again After B_6										
B VI$_0$	0·0614	·003568	61·4	0	0	329·5	92,400	2·44^{x}	9·16	51
B VI$_1$	0·0602	·002846	68·8	20·2	20·2	326·0	114,500	0·22	0·88	41
B VI$_2$	0·0503	·001987	77·7	44·2	30·2	270·0	136,000	0·21	0·84	41
B VI$_3$	0·0470	·001735	80·2	51·3	12·7	241·0	139,000	0·29	1·16	34½
B VI$_4$	0·0413	·001340	84·4	62·5	22·8	198·0	147,800	0·14^{x}	0·56^{x}	37
B VI$_5$	0·0320	·0008042	89·9	77·4	40·0	133·5	166,000	0·14	0·56	24
B VI$_6$	0·0266	·0005557	92·5	84·3	30·9	103·0	185,200	0·14	0·56	23
B VI$_7$	0·0233	·0004264	95·5	88·0	23·3	Failed, when a little through.				

Note: x denotes "Beyond gage".

·45% C Steel Wire Patented

Specimen No.	Wire		% Reduction		Maximum	Tensile	Elongation		Torsion
	Diameter inch	Area Sq. inch	Overall	Successive	Load, lbs.	Strength lbs/□"	in 25" inch	in 25" %	100 Diam. Twists
C_0	0·112	0·00985	0	0	987	100,200	2·55	10·2	47
C_1	0·095	0·00709	28·0	28·0	—	—	—	—	—
C_2	0·085	0·00567	42·4	19·9	821	144,500	0·45	1·8	39
C_3	0·080	0.00503	49·0	11·4	—	—	—	—	—
C_4	0·072	0·00407	58·7	19·0	—	—	—	—	—
C_5	0·068	0·00363	63·2	10·8	585	161,000	0·45	1·8	37
C_6	0·058	0·00264	73·1	27·2	—	—	—	—	—
C_7	—	—	—	—	—	—	—	—	—
C_8	0·047	0·00173	82·3	34·3	—	—	—	—	—
C_9	0·038	0·00113	88·5	34·6	224	193,000	0·17	0.68	16·5
C_{10}	0·029	0·000661	93·2	41·7	156	236,000	0·068	0·24	13·5

·45% C Steel Wire Patented

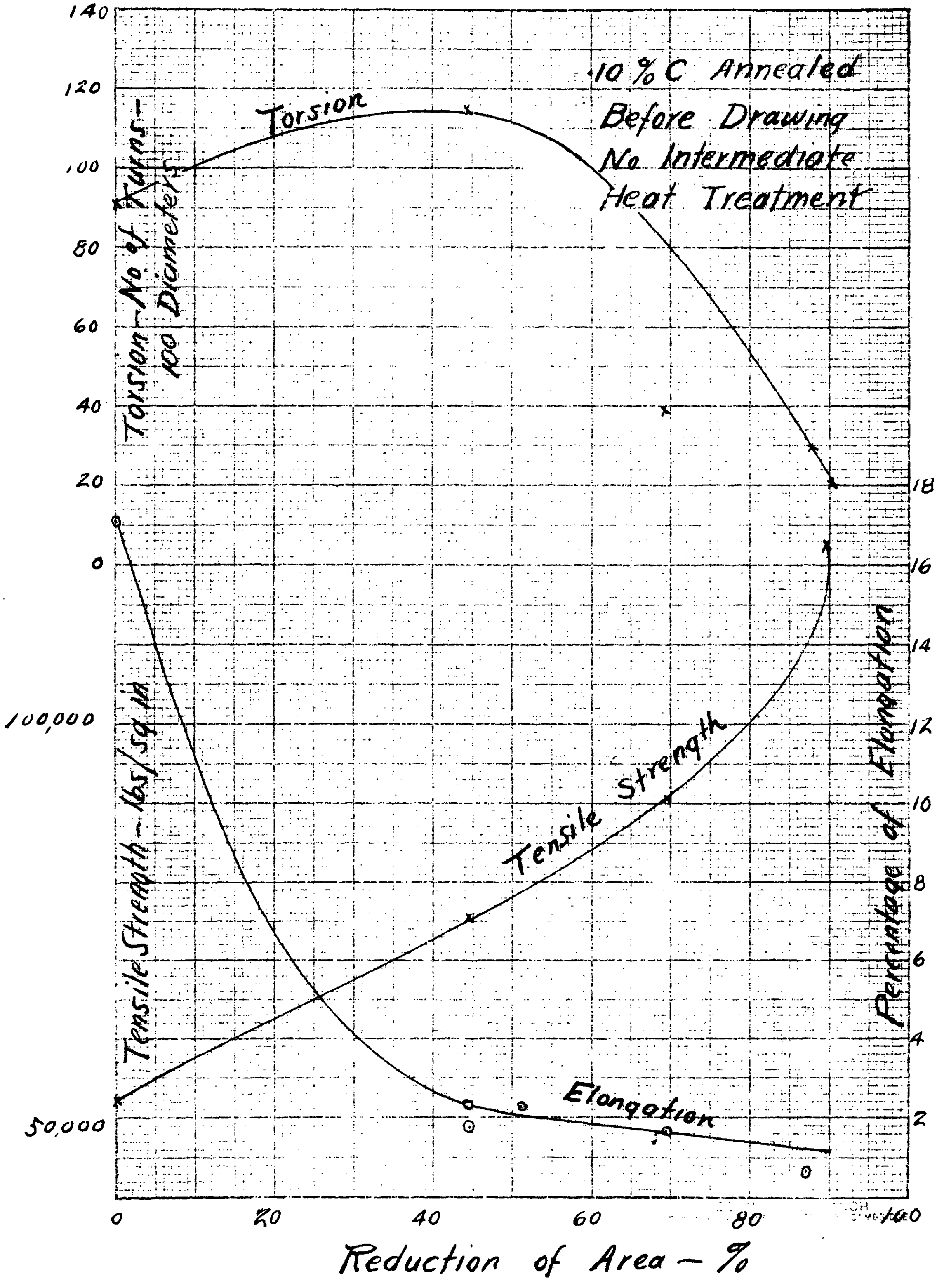
Specimen No.	Wire		% Reduction			Maximum Load, lbs.	Tensile Strength lbs./□"	Elongation, 25"		Torsion 100 Diam Twists
	Diameter Inch	Area Sq. inch	Over-all	After Intermed. Patent.	Successive			Inch	%	
Patented Again After C_{10}										
CX_0	0.029	.000661	93.2	0	0	73	111,000	1.45	5.8	49
CX_1	0.0279	.000611	93.8	7.56	7.56	73	120,000	.10	0.4	42.5
CX_2	0.0221	.000384	96.2	41.9	37.1	60.0	156,000	.11	0.44	40.5
CX_3	0.0213	.000356	96.4	46.1	7.3	54.9	154,600	.17 x	0.68	29.5
CX_4	0.0165	.000214	97.7	67.6	39.9	36.5	170,000	.08 x	0.32	32.5
Patented Again After C_9										
CIX_0	0.0380	.001130	88.5	0	0	120	106,000	1.60	6.40	30
CIX_1	0.0327	.000840	91.3	25.6	25.6	118	140,500	.08	.32	46.5
CIX_2	0.0279	.000611	93.8	46.0	27.3	91.3	149,000	.10 x	.40	38.0
CIX_3	0.0226	.000401	96.0	64.5	34.4	67.7	168,000	.175 x	.70	28.0
CIX_4	0.0213	.000356	96.4	68.5	11.2	61.5	173,000	.36	1.44	14.5
CIX_5	0.0165	.000214	97.8	81.0	40.0	40.8	191,000	.12	.48	5.0

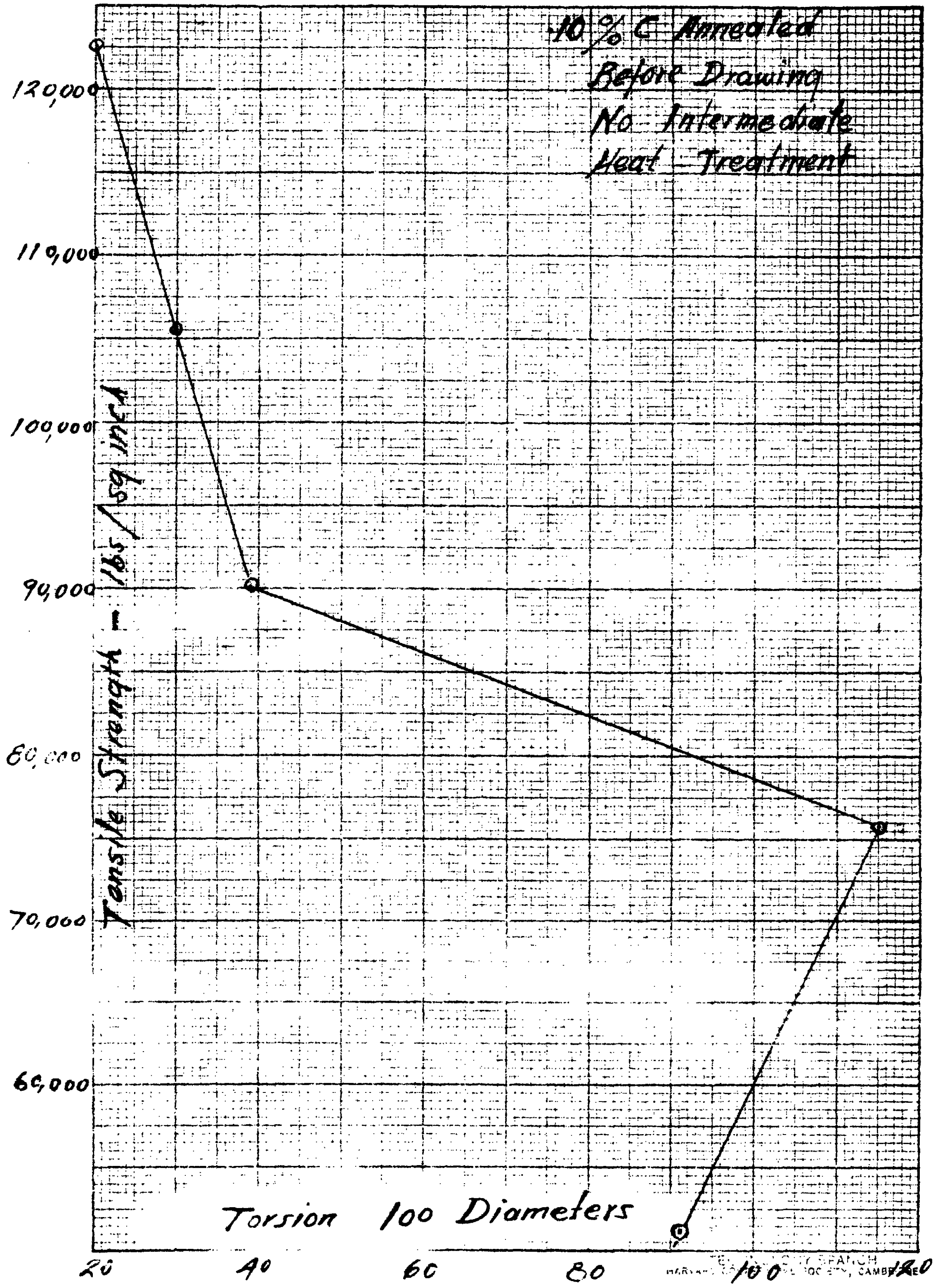
x Break Beyond Gage

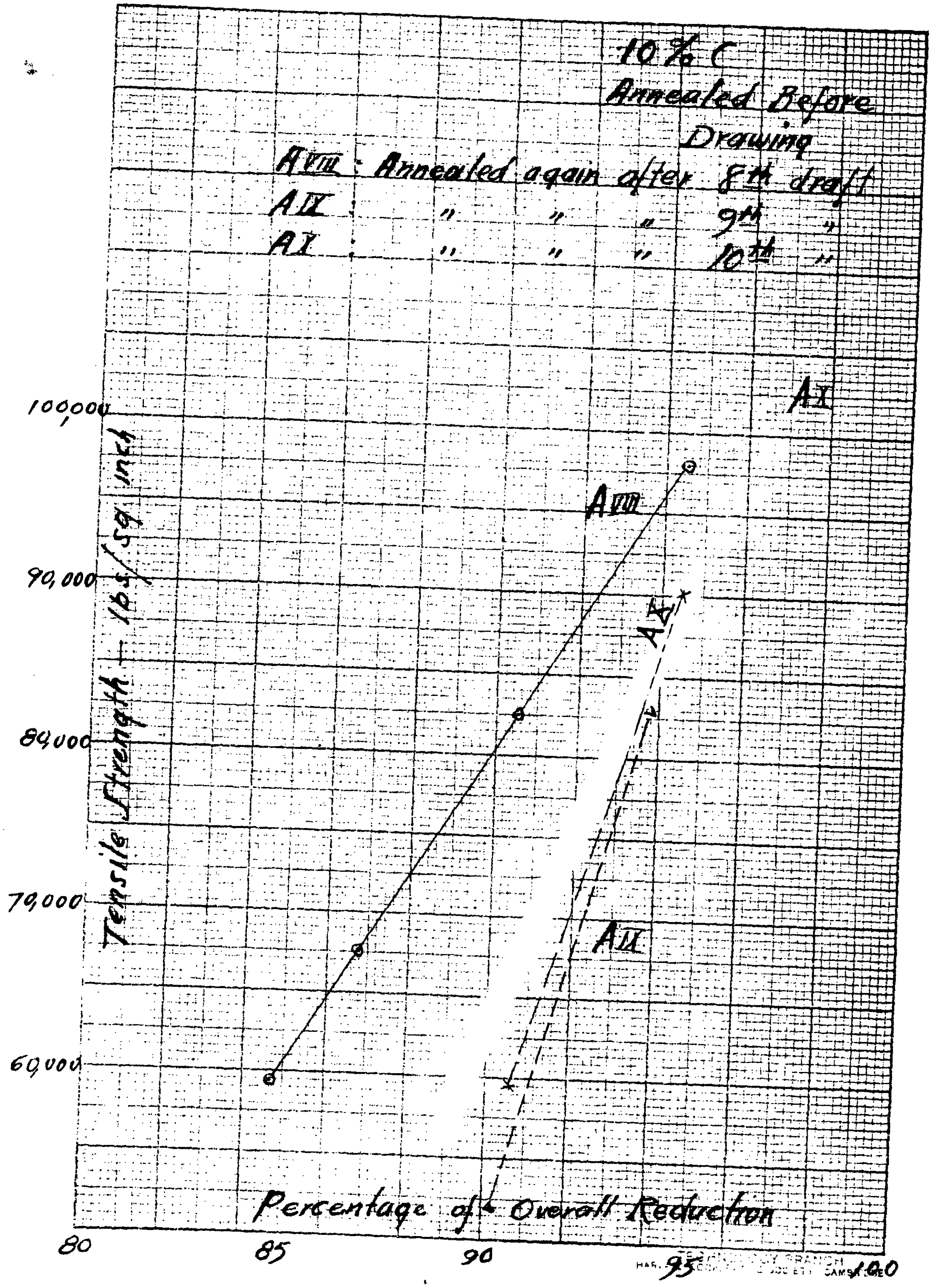
·45% C Steel Wire Patented

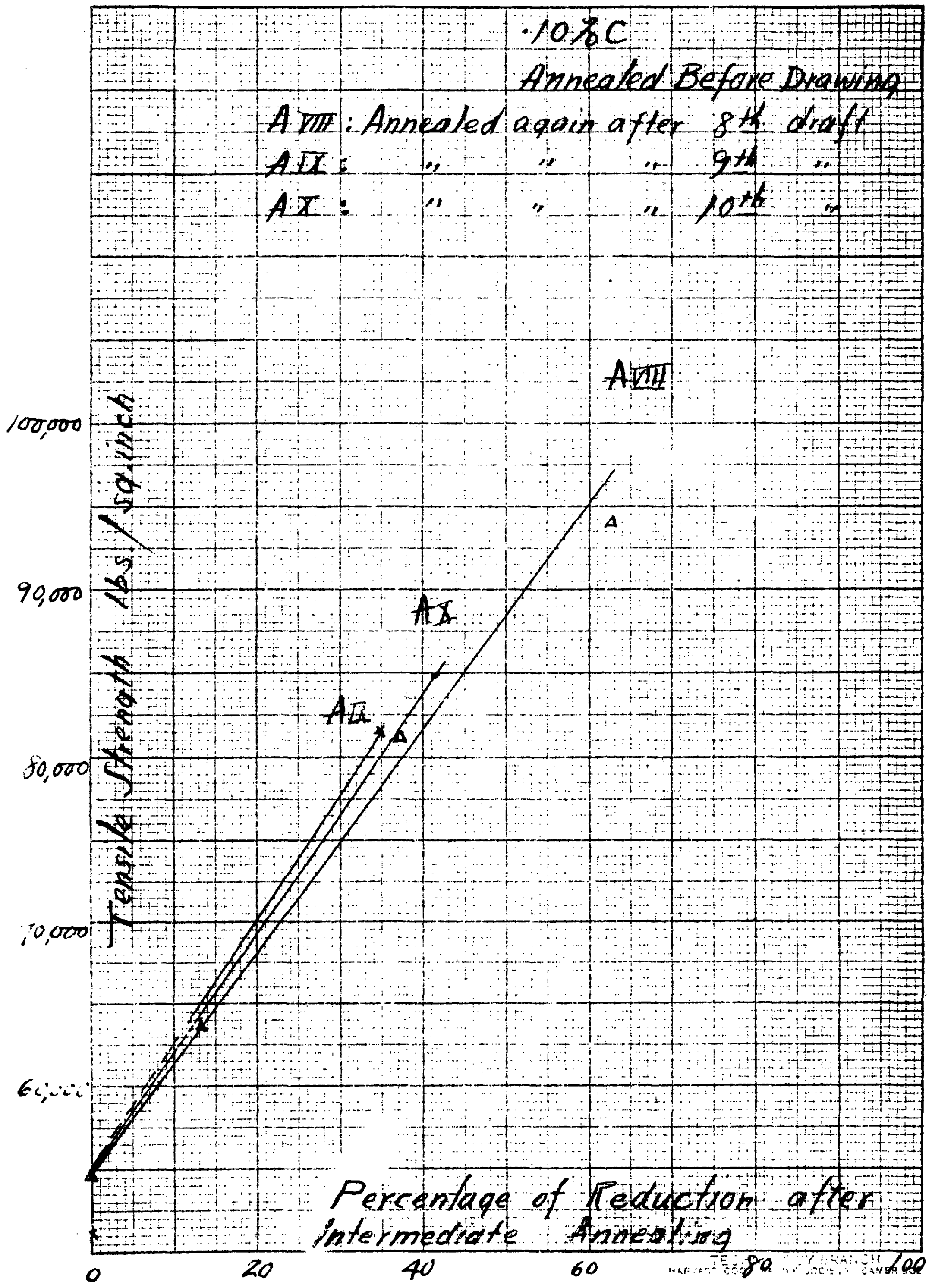
Specimen No	Wire		% Elongation			Maximum Load lbs.	Tensile Strength lbs/□"	Elongation 25"		Torsion 100 Diam Twists
	Diameter Inch	Area Sq. Inch	Over-all	After Intermed. Patent	Successive			Inch	%	
Patented Again After C_8										
C VIII_0	·0468	·00172	82·6	0	0	182·5	106,000	1·69	6·72	41·0
C VIII_1	·0389	·00119	88·0	30·8	30·8	162·5	135,000	·09	·36	46·5
C VIII_2	·0327	·00084	91·5	51·1	29·4	127·5	152,000	·04 x	·16	46·5
C VIII_3	·0279	·000611	93·8	64·5	27·3	101·0	165,000	·12	·48	22·5
C VIII_4	·0225	·000398	95·9	76·8	34·9	68·0	171,000	·04	·16	13·5
C VIII_5	·0213	·000356	96·5	79·3	10·6	66·0	185,000	—	—	26·0
Patented Again After C_6										
C VI_0	·0583	·00267	73·0	0	0	290	108,700	1·48	5·92	48
C VI_1	·0473	·00176	82·1	19·0	19·0	242	138,500	·13	·52	37
C VI_2	·0413	·00134	86·4	29·2	23·9	194·5	145,000	·08 X	·32	36·5
C VI_3	·0330	·00085	91·4	43·4	36·2	144·5	169,000	·07	·28	39·0
C VI_4	·0278	·000607	93·6	52·3	29·0	129·2	213,000	·175	·70	29·0
C VI_5	·0220	·000384	96·1	62·2	36·7	80·0	208,000	·20	·80	12·0
C VI_6	·0216	·000366	96·3	63·0	47·0	65·0	177,500	0	0	24·5

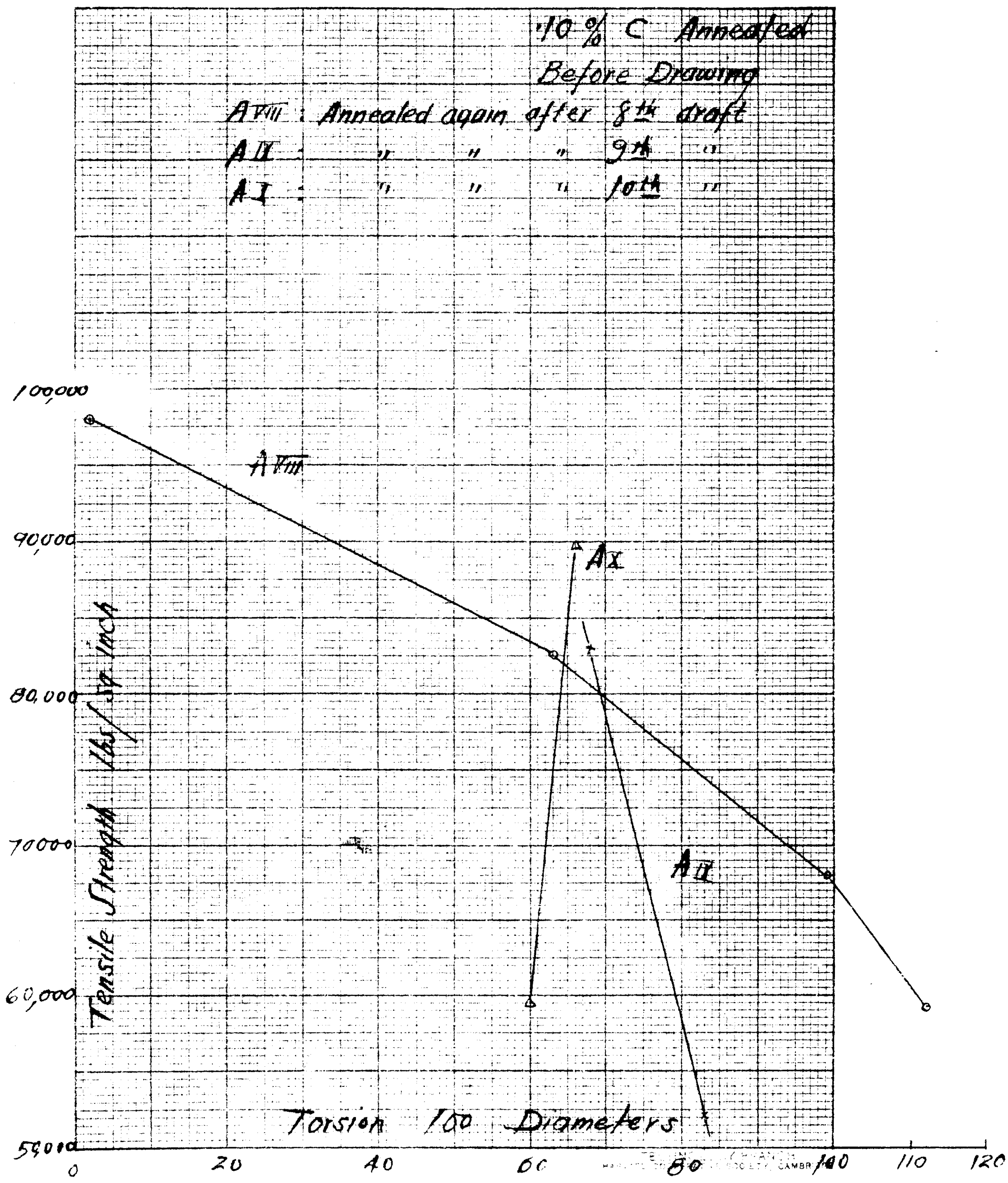
X Break Beyond Gage

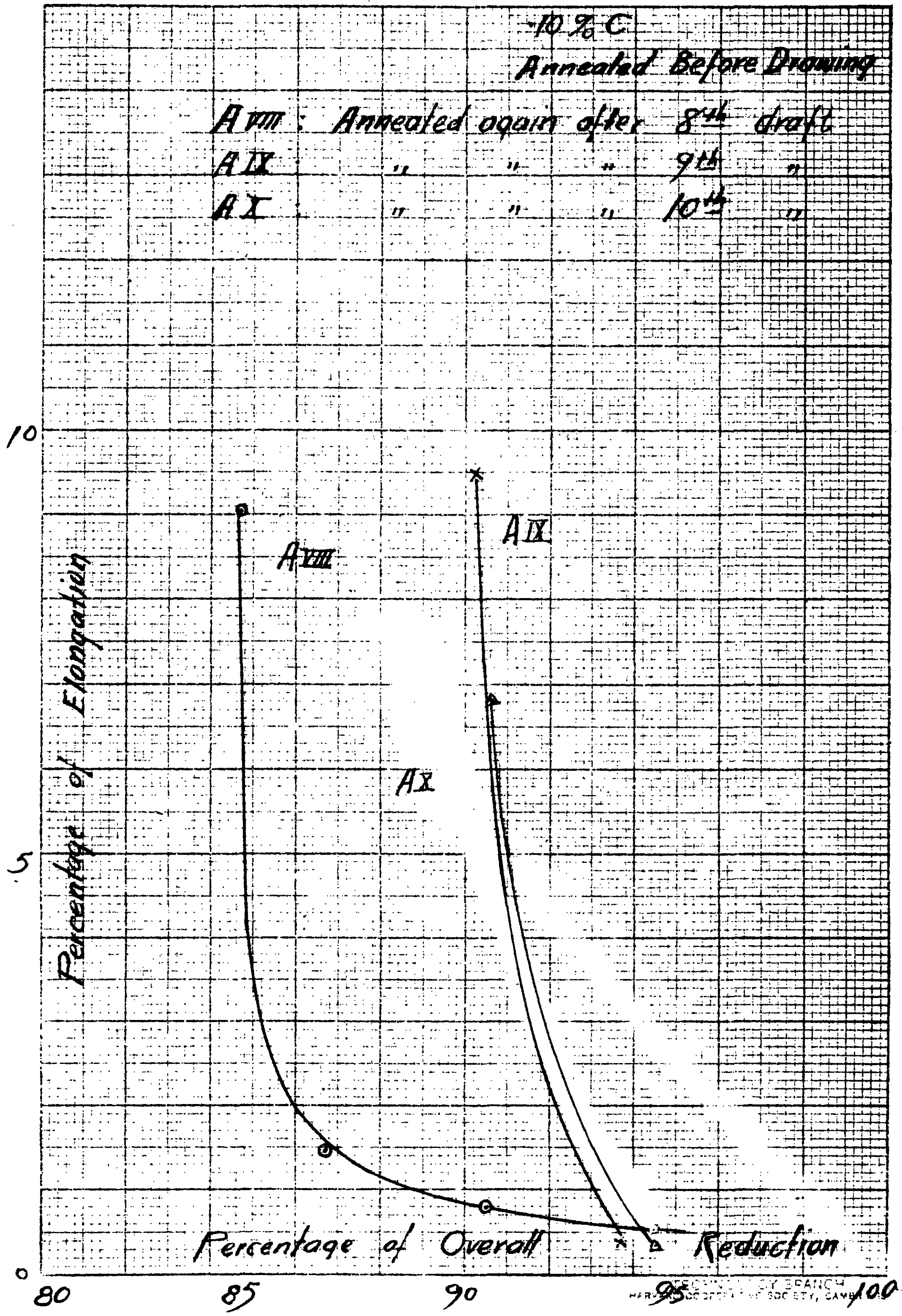

.10 % C Annealed
Before Drawing
No Intermediate
Heat Treatment
Torsion
Tensile Strength
Elongation
Torsion - No of Turns - 100 Diameters
Tensile Strength - lbs/sq in
Percentage of Elongation
Reduction of Area - %
140
120
100
80
60
40
20
0
100,000
50,000
18
16
14
12
10
8
6
4
2
0
20
40
60
80
100

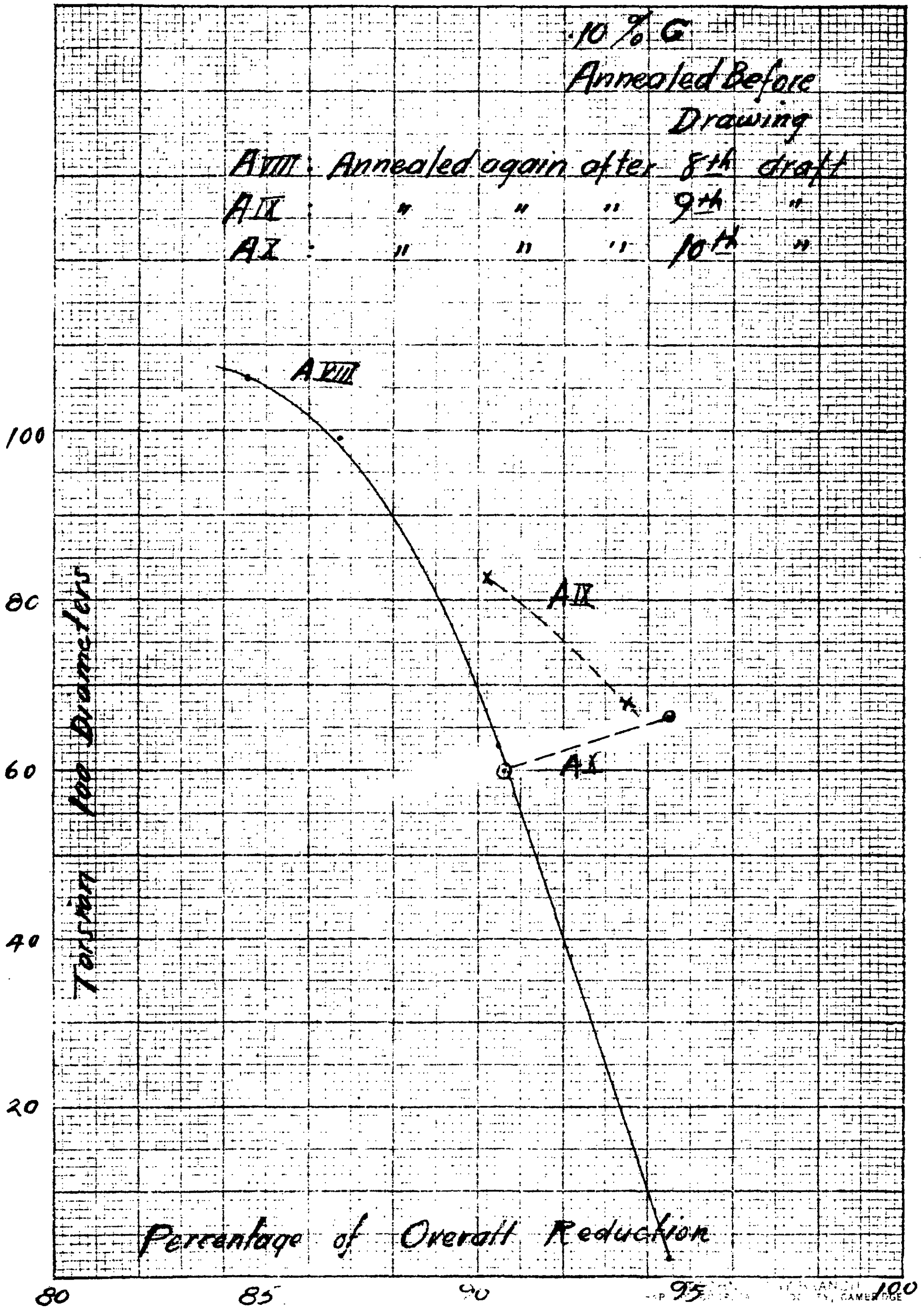

.10 % C Annealed
Before Drawing
No Intermediate
Heat - Treatment
Tensile Strength - lbs / sq inch
120,000
110,000
100,000
90,000
80,000
70,000
60,000
Torsion 100 Diameters
20
40
60
80
100
120

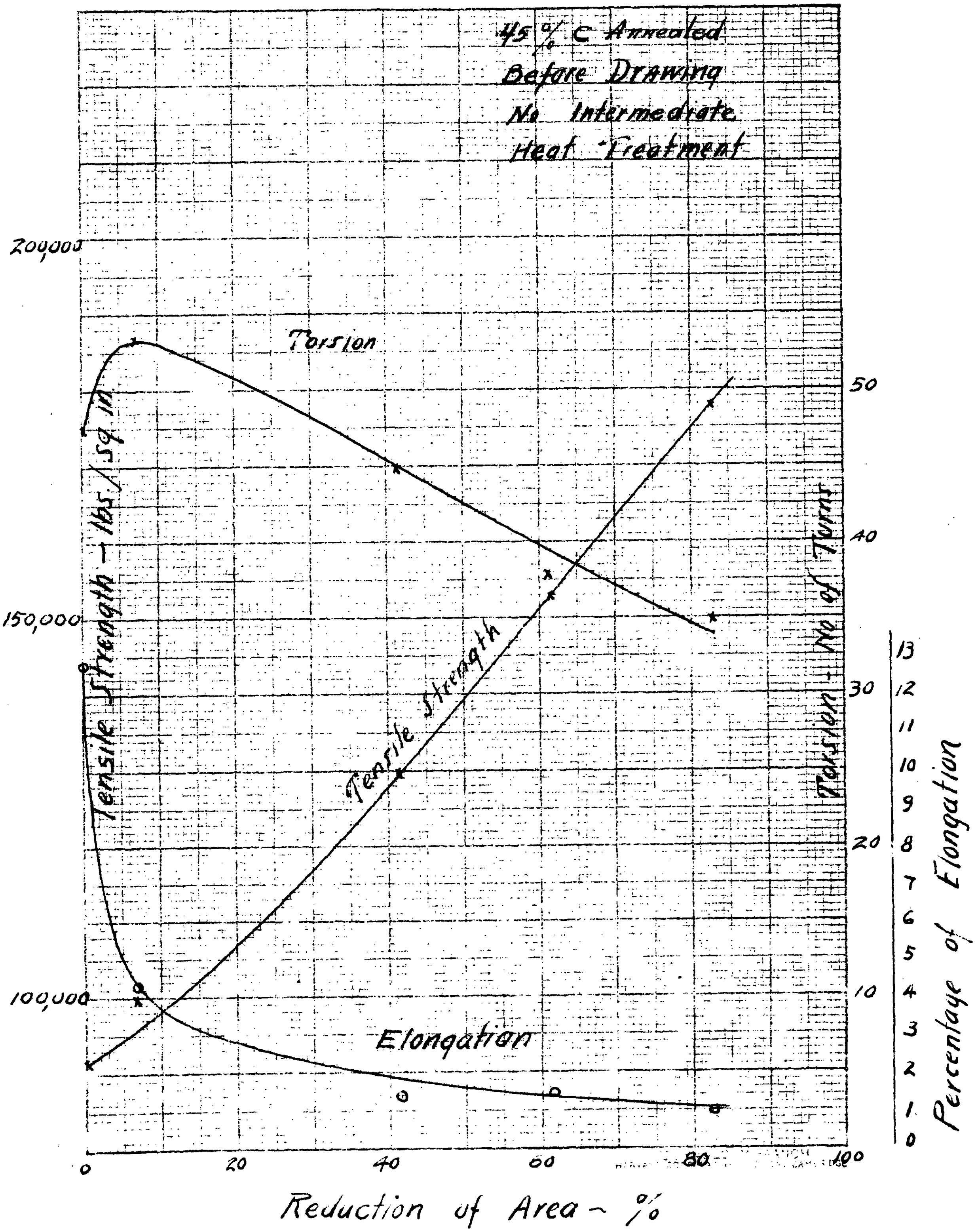

.10% C
Annealed Before
Drawing
AVIII : Annealed again after 8th draft
AIX : " " " 9th "
AX : " " " 10th "
AX
AVIII
AX
AIX
100,000
90,000
80,000
70,000
60,000
Tensile Strength - lbs/sq inch
Percentage of Overall Reduction
80
85
90
95
100

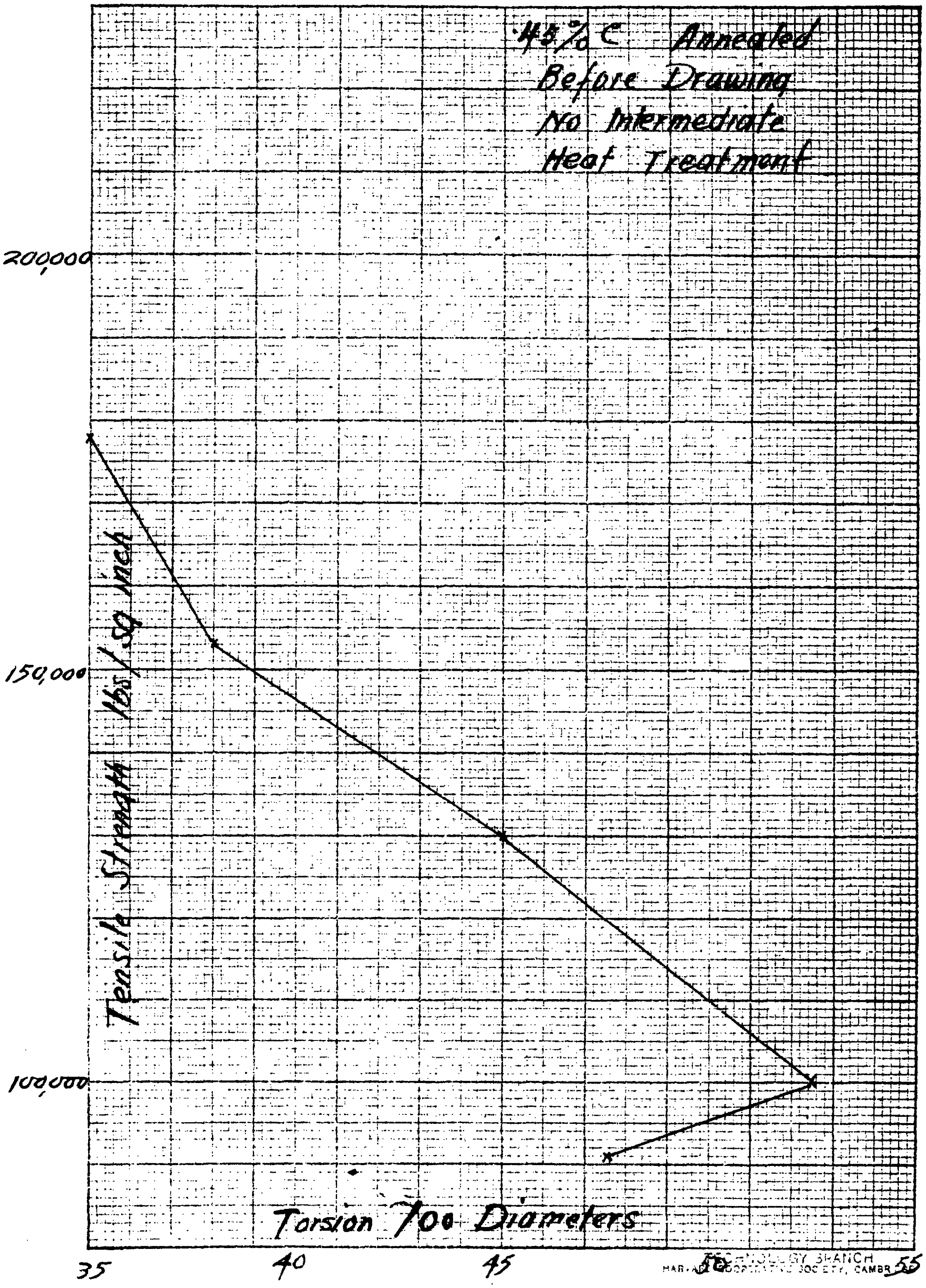

·10%C
Annealed Before Drawing
A VIII : Annealed again after 8th draft
A IX : " " " 9th "
A X : " " " 10th "
A VIII
A X
A IX
Tensile Strength lbs / sq. inch
100,000
90,000
80,000
70,000
60,000
Percentage of Reduction after Intermediate Annealing
0
20
40
60
80
100

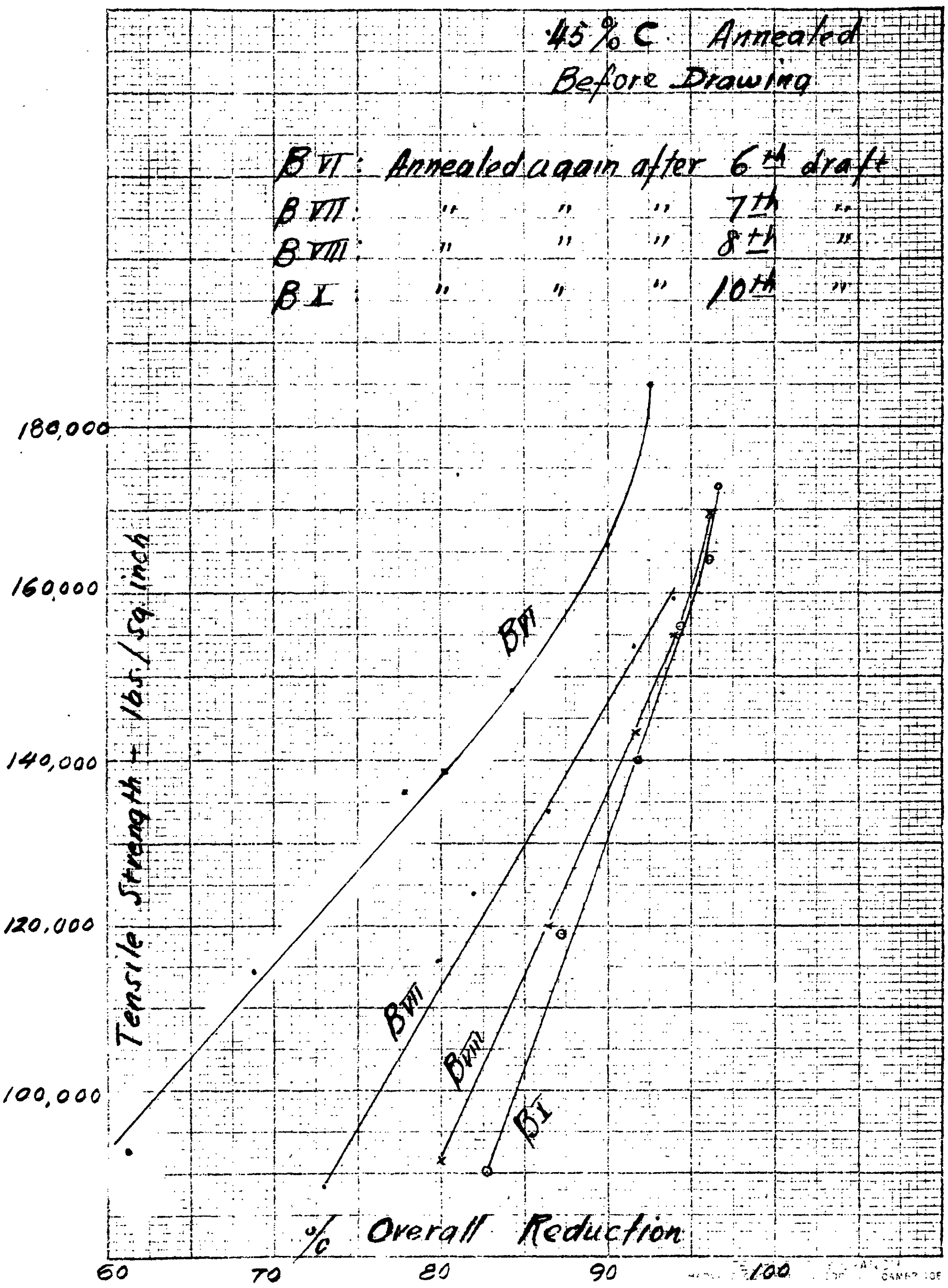

·10 % C Annealed
Before Drawing
AVIII : Annealed again after 8th draft
AIX : " " " 9th "
AX : " " " 10th "
AVIII
AX
AIX
Tensile Strength lbs/sq inch
Torsion 100 Diameters
100,000
90000
80,000
70000
60,000
50000
0
20
40
60
80
100
110
120


.10 % C
Annealed Before Drawing
A VIII : Annealed again after 8th draft
A IX " " " 9th "
A X " " " 10th "
A VIII
A IX
A X
Percentage of Elongation
Percentage of Overall Reduction
0
5
10
80
85
90
95
100
TECHNOLOGY BRANCH
HARVARD COOPERATIVE SOCIETY, CAMBRIDGE

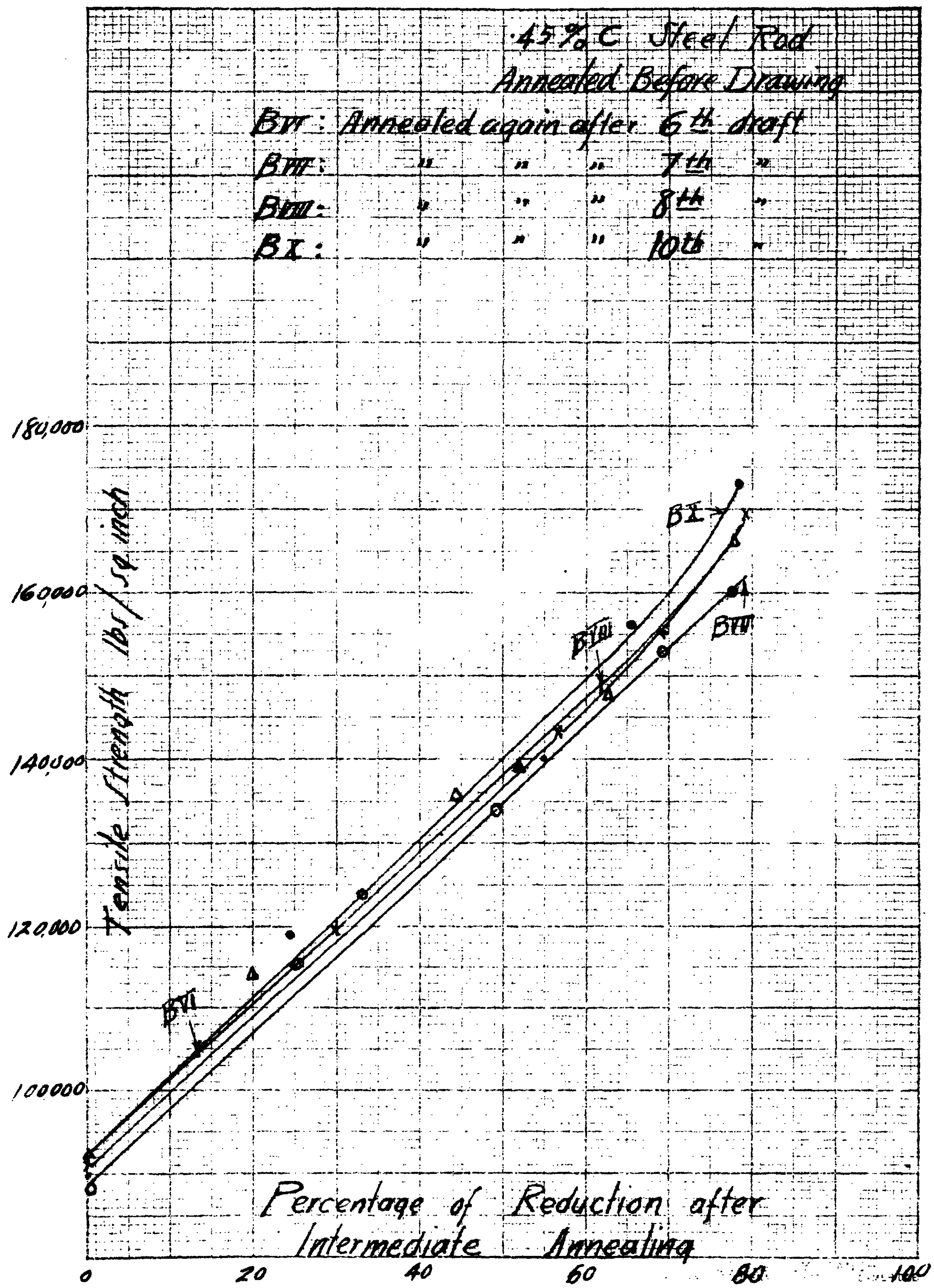

.10 % G
Annealed Before Drawing
AVIII : Annealed again after 8th draft
AIX : " " " 9th "
AX : " " " 10th "
AVIII
AIX
AX
100
80
60
40
20
Torsion per 100 Diameters
Percentage of Overall Reduction
80
85
90
95
100

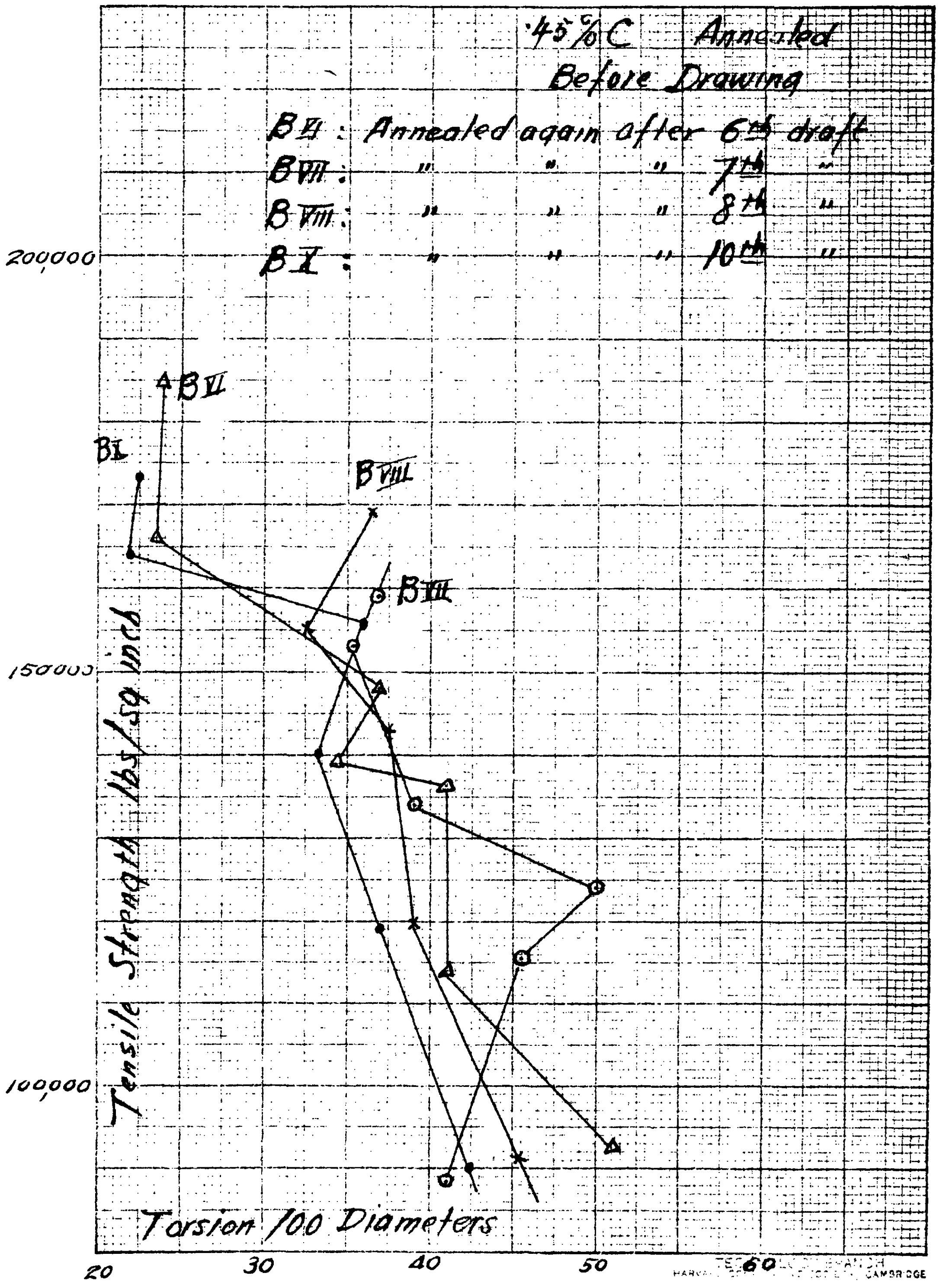

45% C Annealed
Before Drawing
No Intermediate
Heat Treatment
Torsion
Tensile Strength
Elongation
Tensile Strength – lbs./sq. in.
200,000
150,000
100,000
Torsion – No. of Turns
50
40
30
20
10
Percentage of Elongation
13
12
11
10
9
8
7
6
5
4
3
2
1
0
0
20
40
60
80
100
Reduction of Area – %


45% C Annealed
Before Drawing
No Intermediate
Heat Treatment
200,000
150,000
100,000
Tensile Strength lbs/sq inch
Torsion 100 Diameters
35
40
45
50
55
TECHNOLOGY BRANCH
HARVARD COOPERATIVE SOCIETY, CAMBR

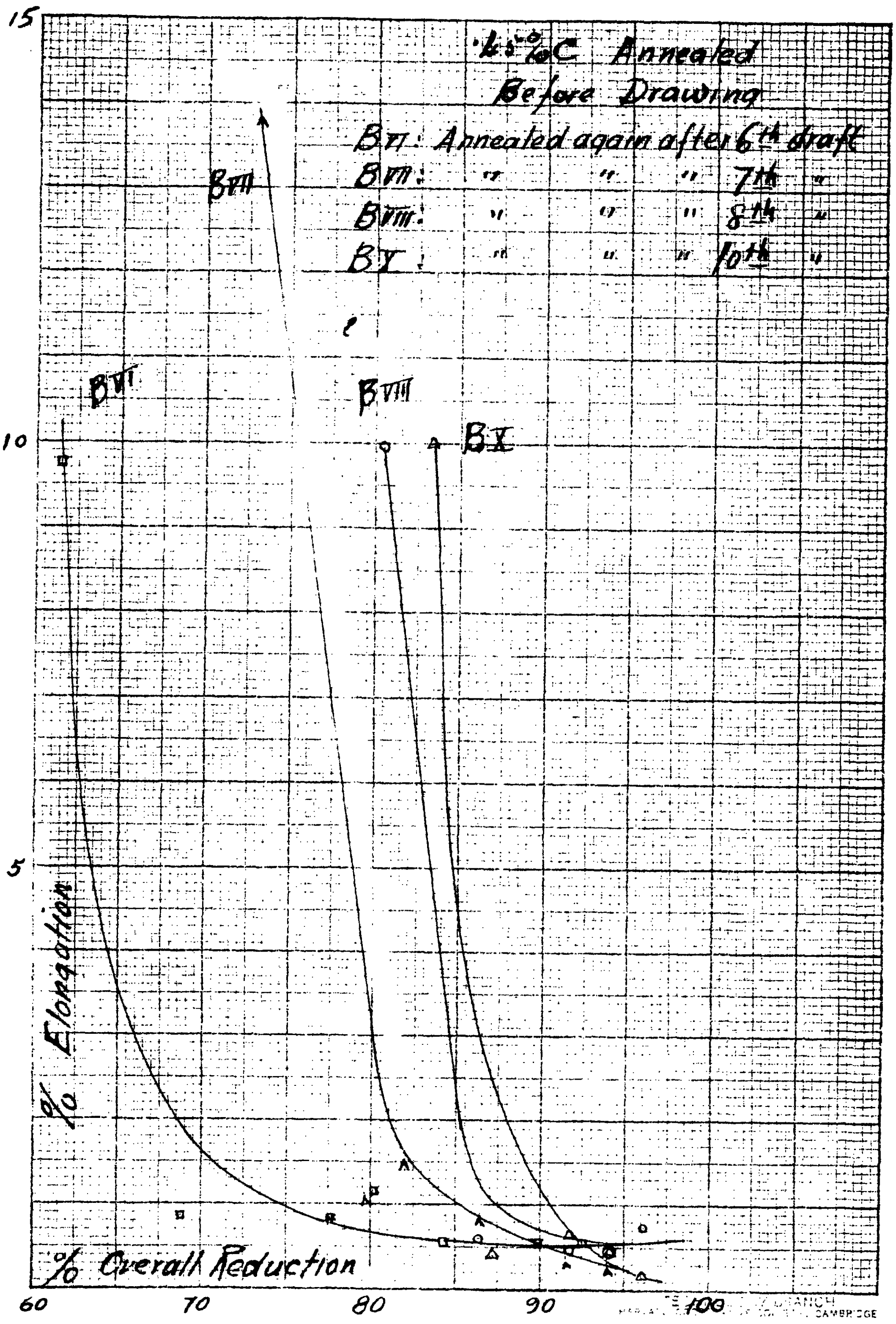


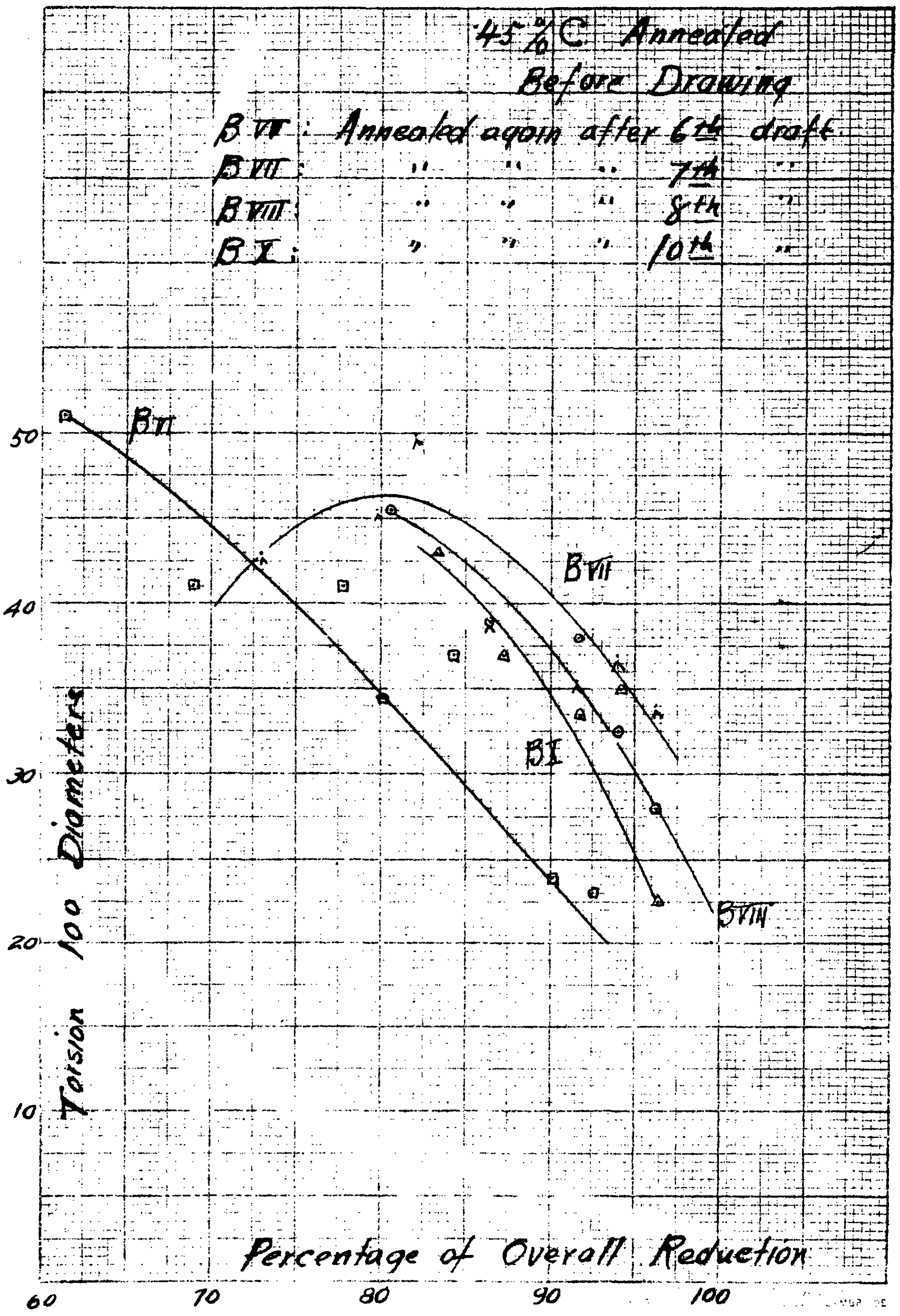
.45% C Annealed
Before Drawing
B VI: Annealed again after 6th draft
B VII: " " " 7th "
B VIII: " " " 8th "
B X: " " " 10th "
180,000
160,000
140,000
120,000
100,000
Tensile Strength - lbs./sq. inch
B VI
B VII
B VIII
B X
% Overall Reduction
60
70
80
90
100

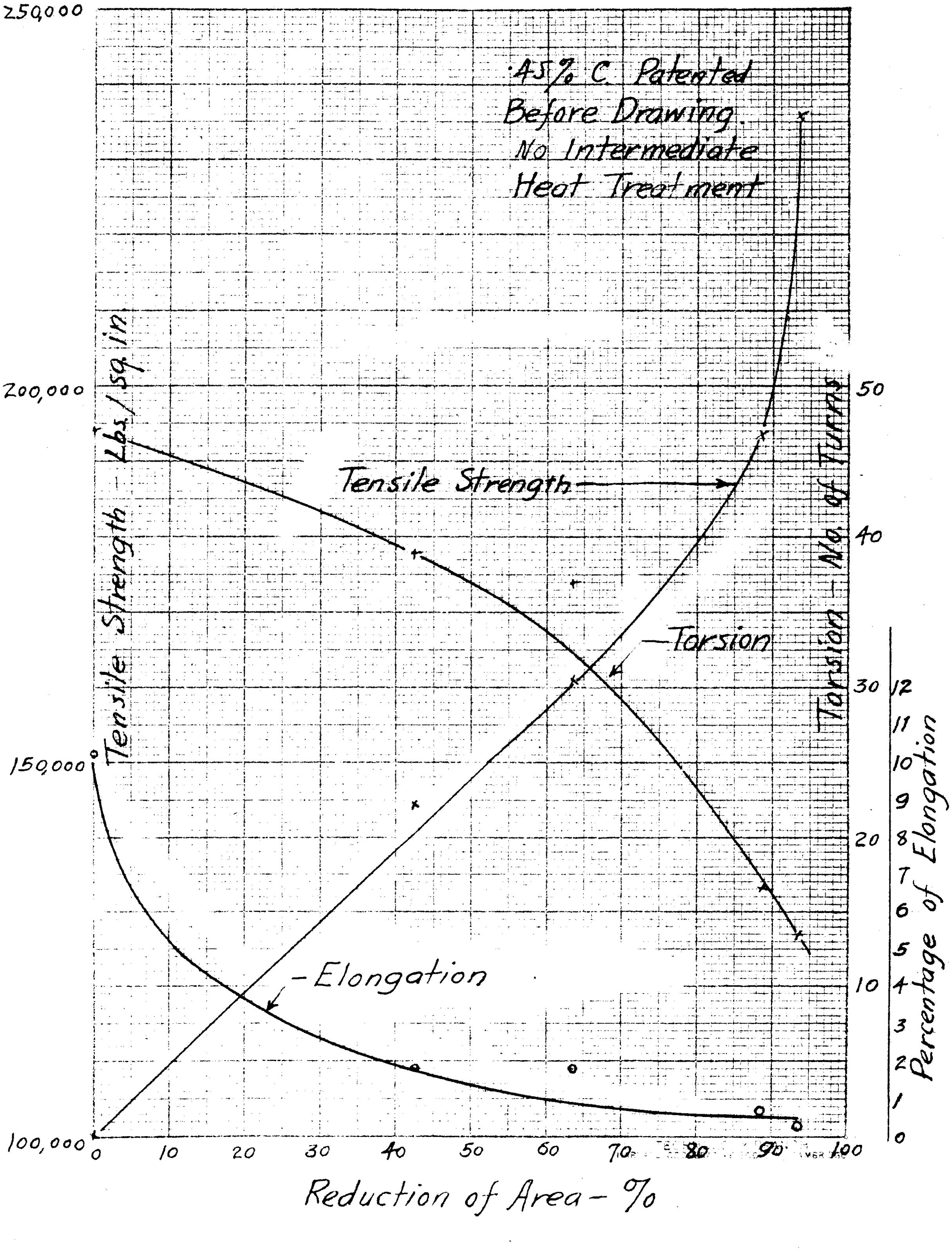

.45% C Steel Rod
Annealed Before Drawing
BVI : Annealed again after 6th draft
BVII: " " " 7th "
BVIII: " " " 8th "
BX: " " " 10th "
Tensile Strength lbs/sq. inch
180,000
160,000
140,000
120,000
100000
BX
BVIII
BVII
BVI
Percentage of Reduction after Intermediate Annealing
0
20
40
60
80
100

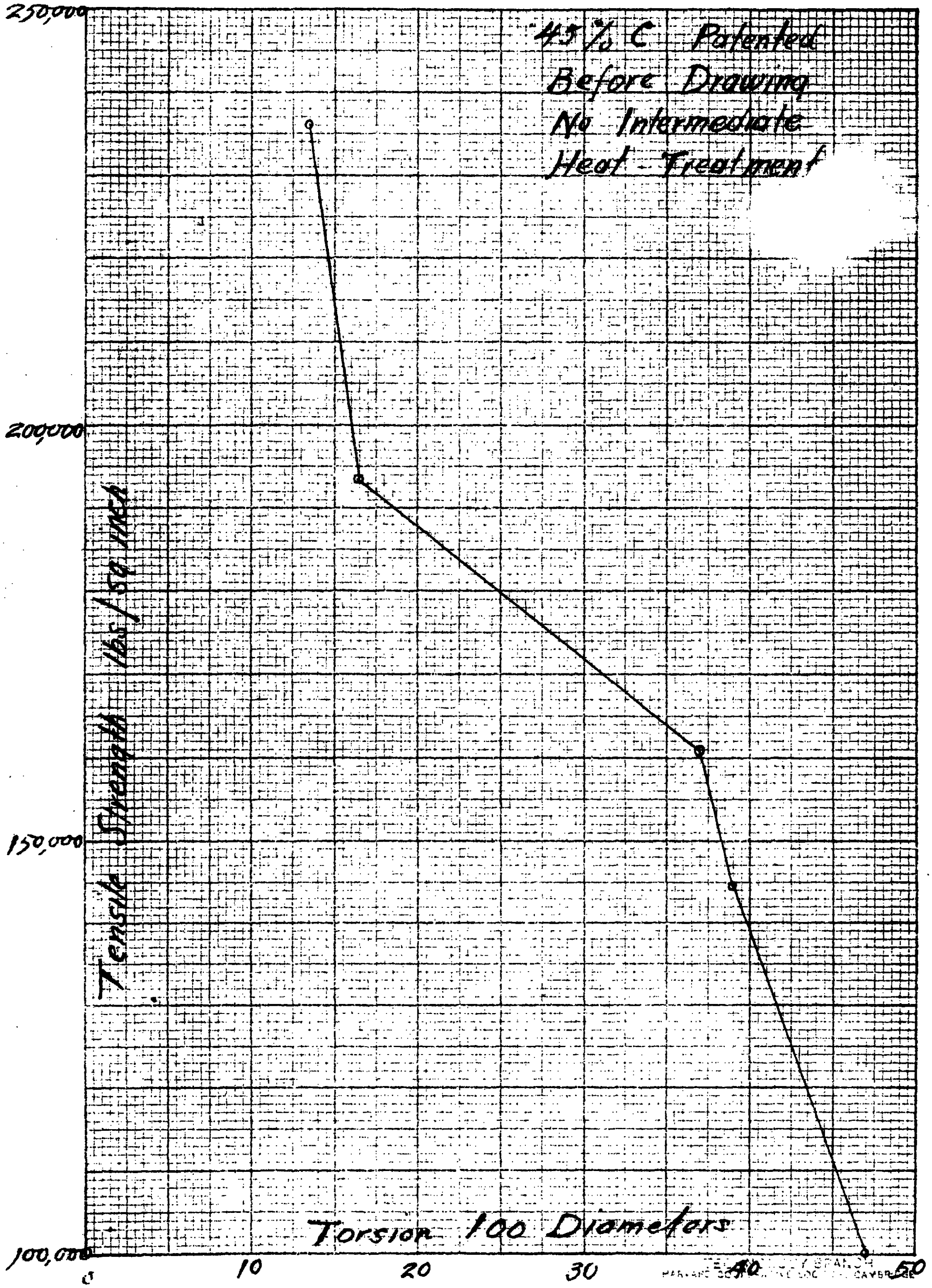


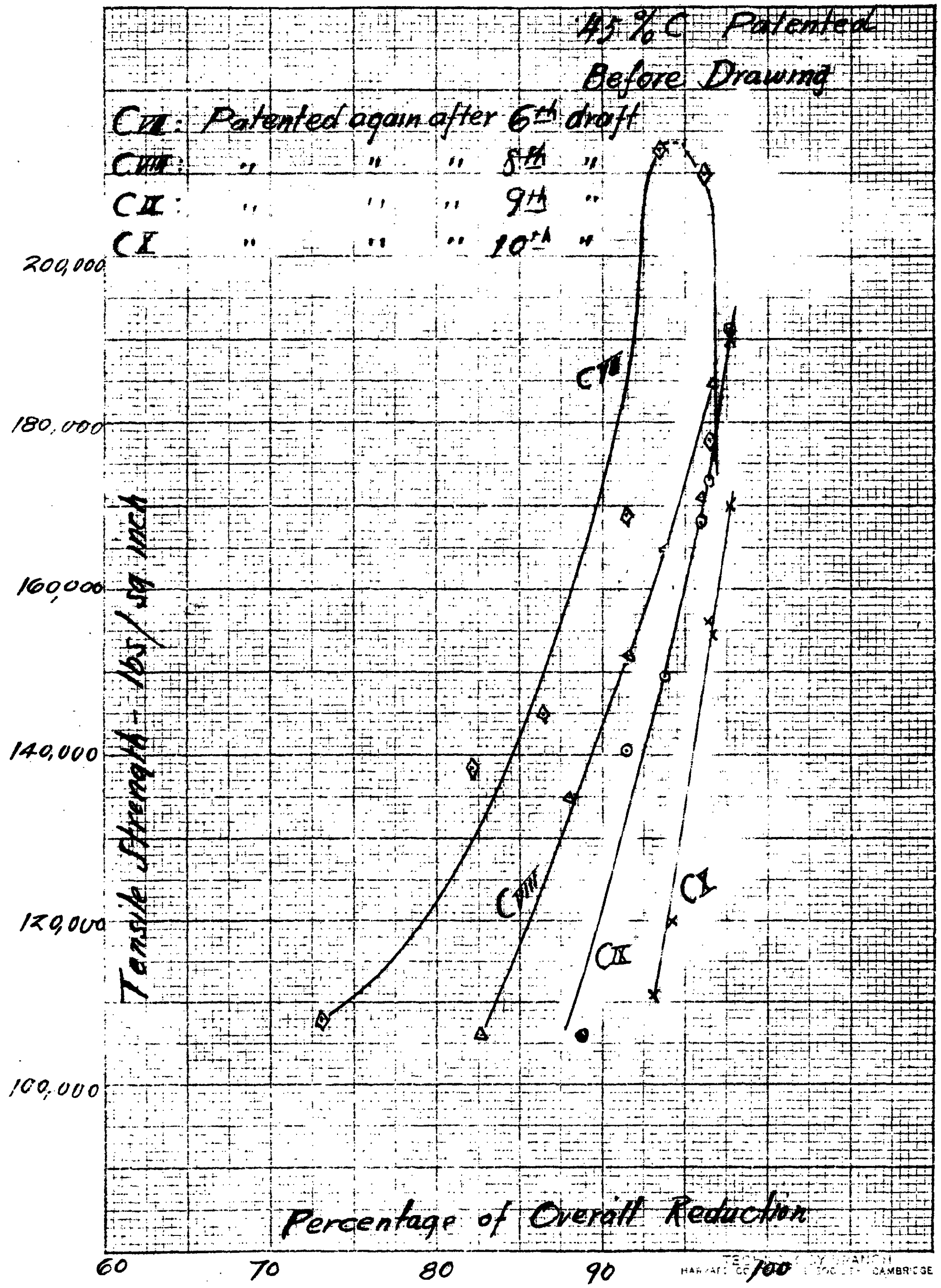
·45% C Annealed
Before Drawing
BVI : Annealed again after 6th draft
BVII : " " " 7th "
BVIII : " " " 8th "
BX : " " " 10th "
BVI
BX
BVIII
BVII
200000
150000
100000
Tensile Strength lbs/sq inch
Torsion 100 Diameters
20
30
40
50
60

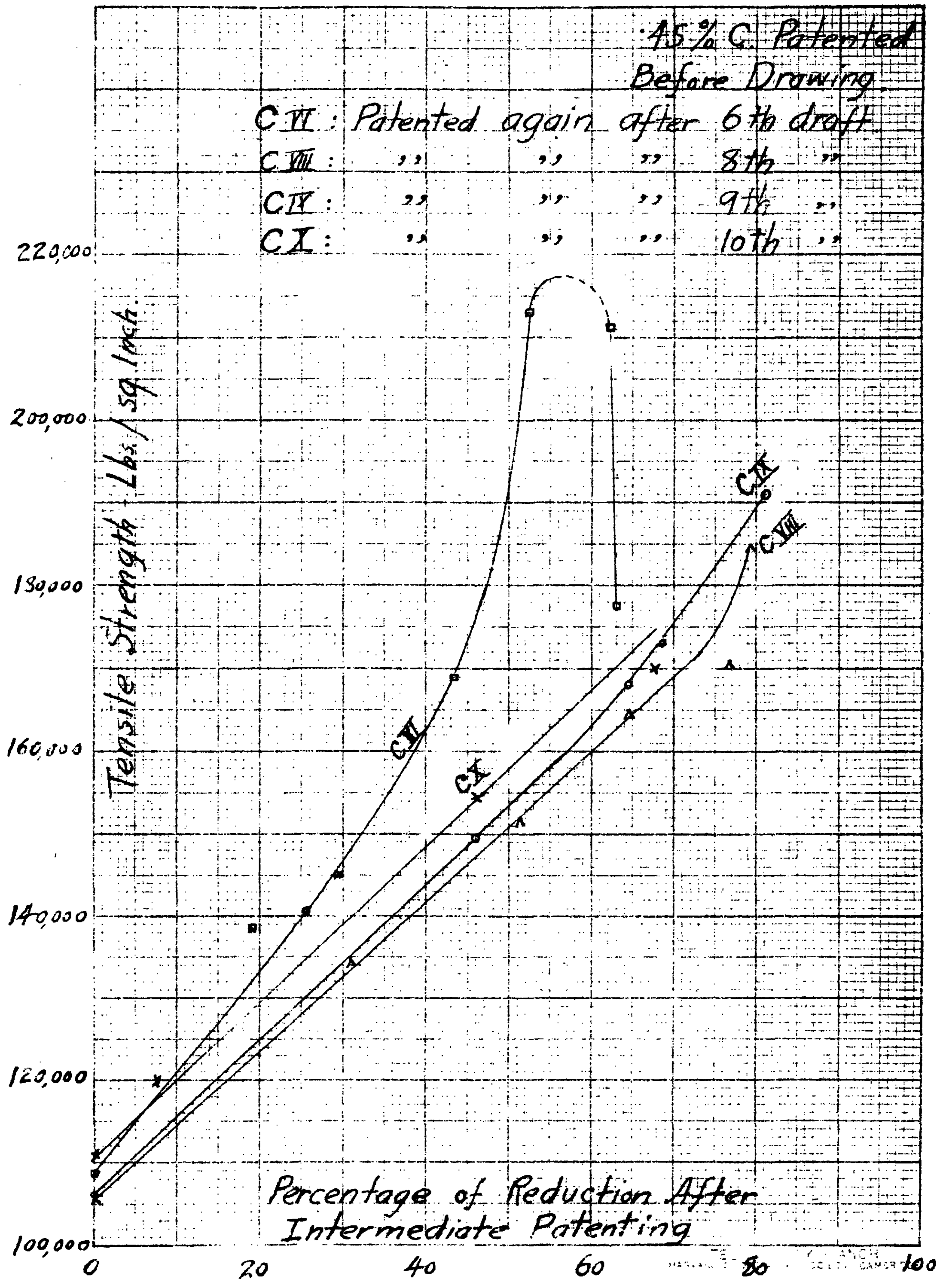

.45% C Annealed
Before Drawing
BVI: Annealed again after 6th draft
BVII: " " " 7th "
BVIII: " " " 8th "
BX: " " " 10th "
BVII
BVI
BVIII
BX
% Elongation
% Overall Reduction
15
10
5
60
70
80
90
100

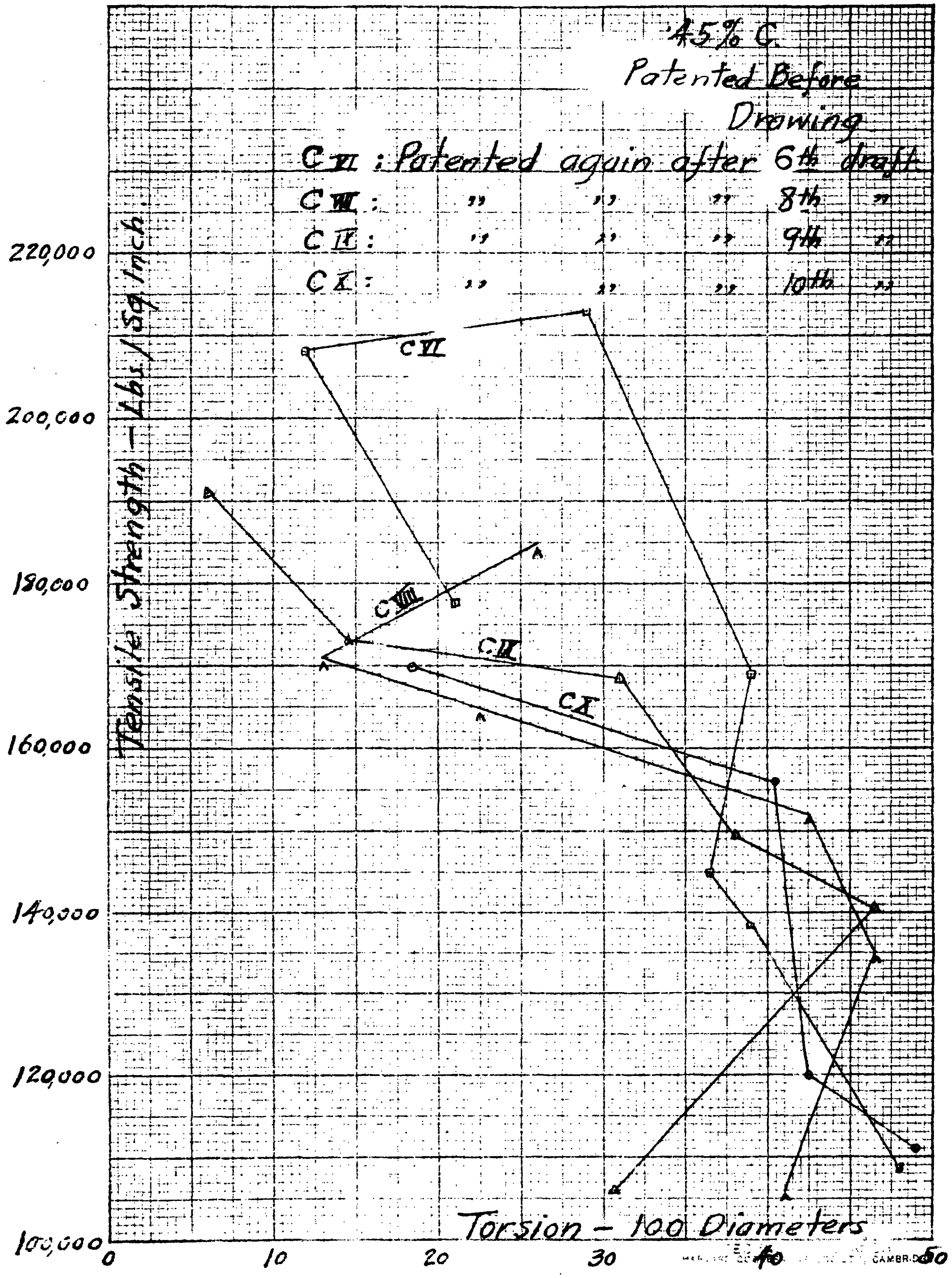

45% C Annealed
Before Drawing
β VI : Annealed again after 6th draft
β VII : " " " 7th "
β VIII : " " " 8th "
β X : " " " 10th "
βVI
βVII
βX
βVIII
50
40
30
20
10
Torsion 100 Diameters
60
70
80
90
100
Percentage of Overall Reduction

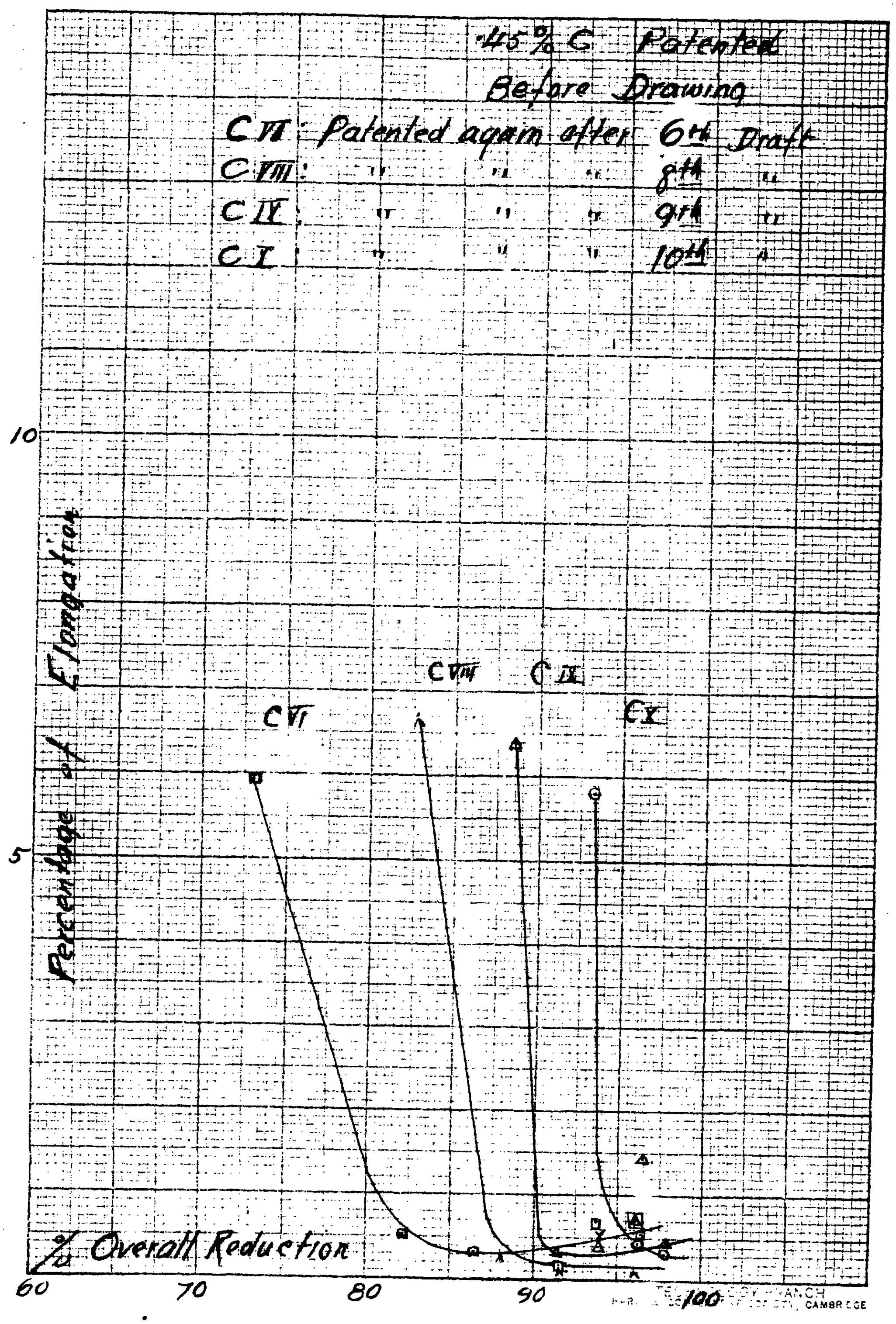

.45% C. Patented
Before Drawing.
No Intermediate
Heat Treatment
Tensile Strength
Torsion
Elongation
Tensile Strength - Lbs./sq.in.
Torsion - No. of Turns
Percentage of Elongation
Reduction of Area - %
250,000
200,000
150,000
100,000
0
10
20
30
40
50
60
70
80
90
100
50
40
30
20
10
12
11
10
9
8
7
6
5
4
3
2
1
0

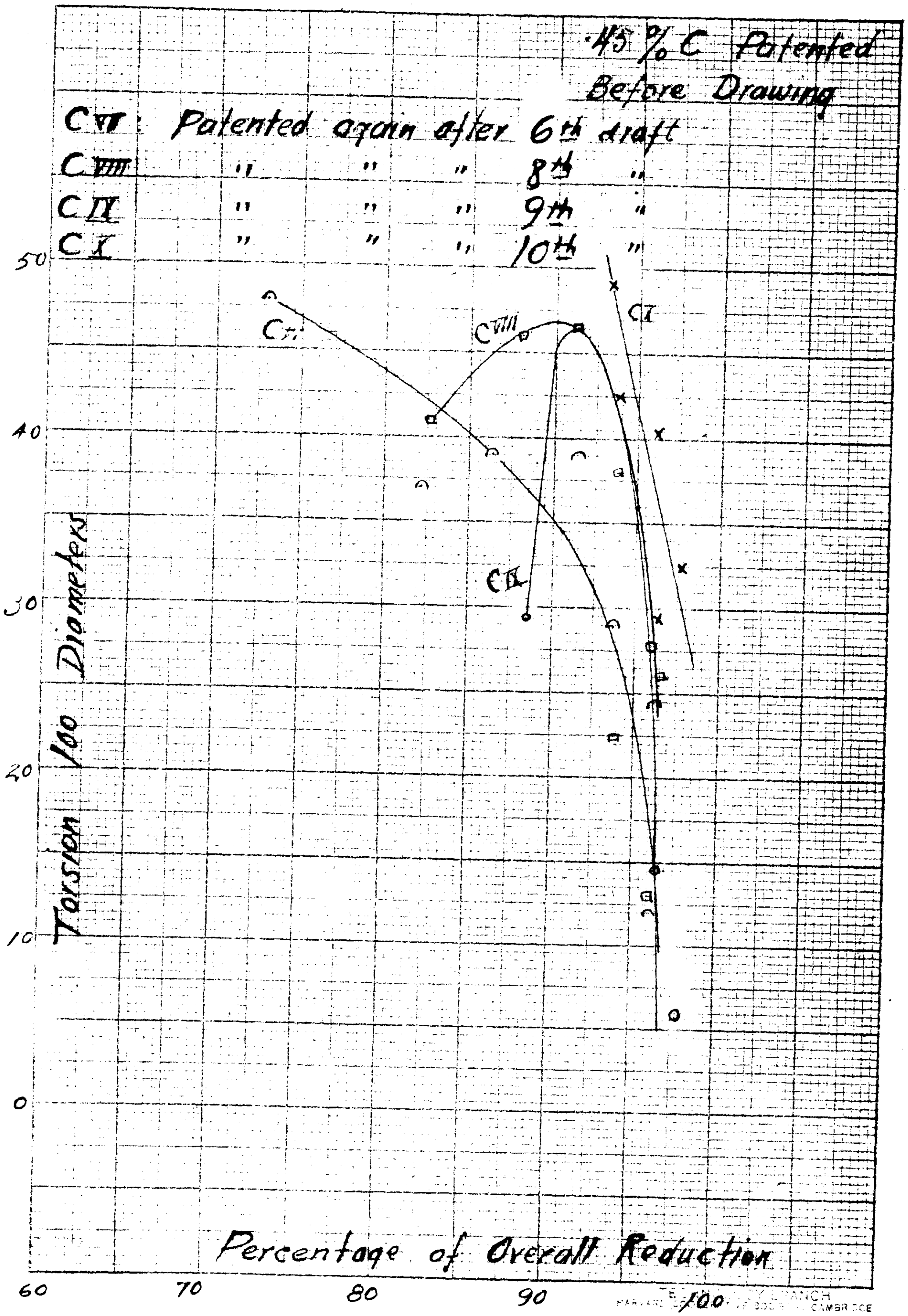

45% C Patented
Before Drawing
No Intermediate
Heat Treatment
Tensile Strength lbs/sq inch
Torsion 100 Diameters
250,000
200,000
150,000
100,000
0
10
20
30
40
50

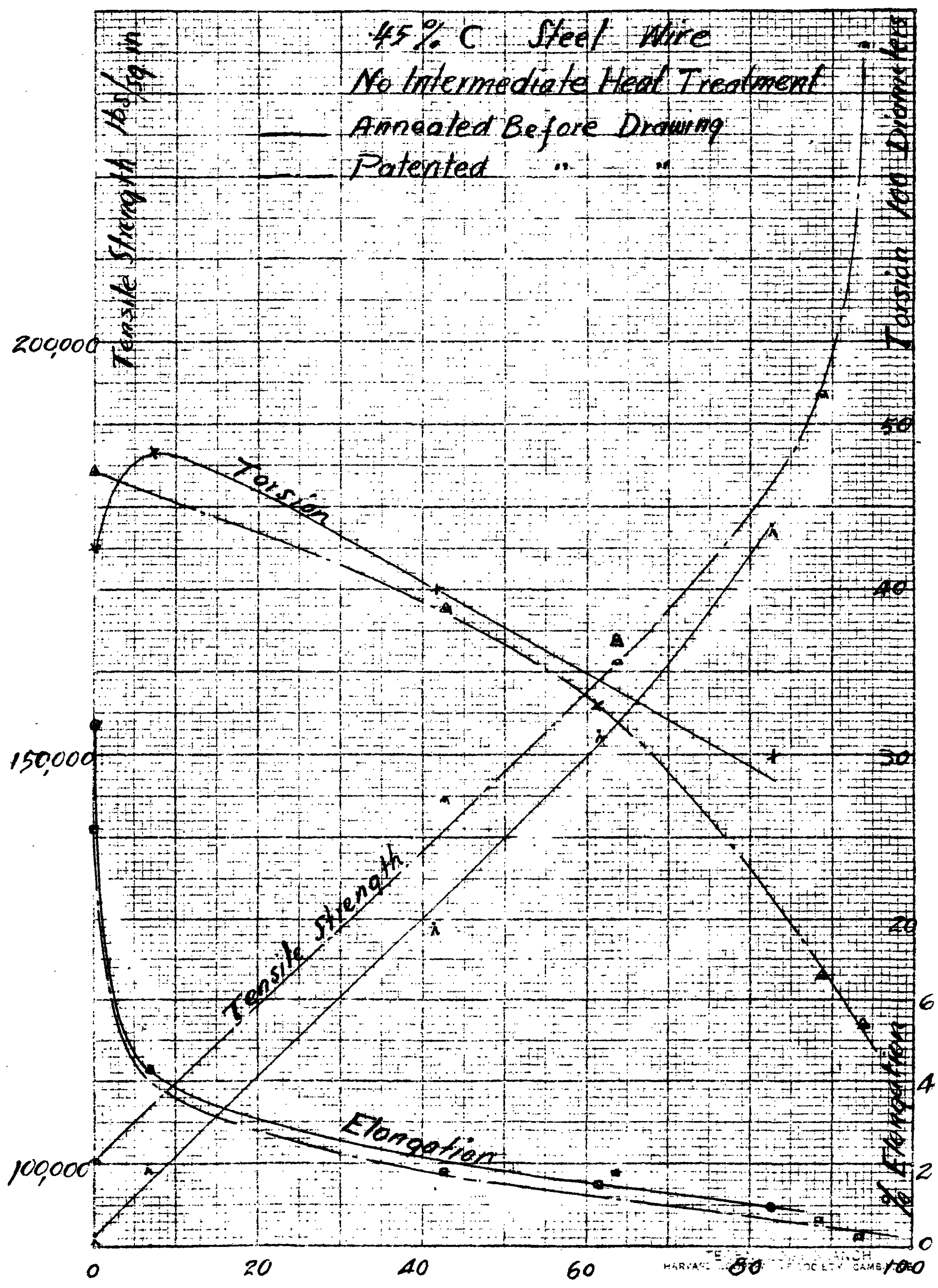

45% C Patented
Before Drawing
CVII: Patented again after 6th draft
CVIII: " " " 8th "
CIX: " " " 9th "
CX " " " 10th "
CVII
CVIII
CIX
CX
200,000
180,000
160,000
140,000
120,000
100,000
Tensile Strength - lbs/sq. inch
Percentage of Overall Reduction
60
70
80
90
100

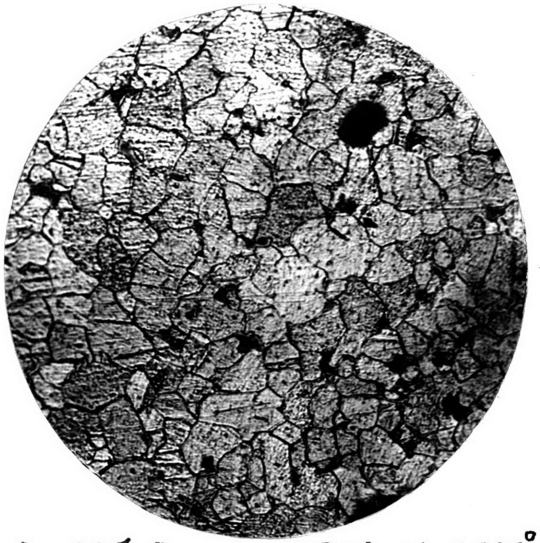

.45% C. Patented
Before Drawing.
C VI : Patented again after 6th draft
C VIII : ,, ,, ,, 8th ,,
C IV : ,, ,, ,, 9th ,,
C X : ,, ,, ,, 10th ,,
Tensile Strength Lbs./sq. Inch.
220,000
200,000
180,000
160,000
140,000
120,000
100,000
0
20
40
60
80
100
C VI
C X
C IV
C VIII
Percentage of Reduction After
Intermediate Patenting


·45% C
Patented Before Drawing
C VI : Patented again after 6th draft
C VIII : ,, ,, ,, 8th ,,
C IX : ,, ,, ,, 9th ,,
C X : ,, ,, ,, 10th ,,
C VI
C VIII
C IX
C X
Tensile Strength – Lbs./Sq. Inch
220,000
200,000
180,000
160,000
140,000
120,000
100,000
Torsion – 100 Diameters
0
10
20
30
40
50


.45% C Patented
Before Drawing
C VI: Patented again after 6th Draft
C VIII: " " " 8th "
C IX: " " " 9th "
C X: " " " 10th "
C VI
C VIII
C IX
C X
10
5
Percentage of Elongation
% Overall Reduction
60
70
80
90
100

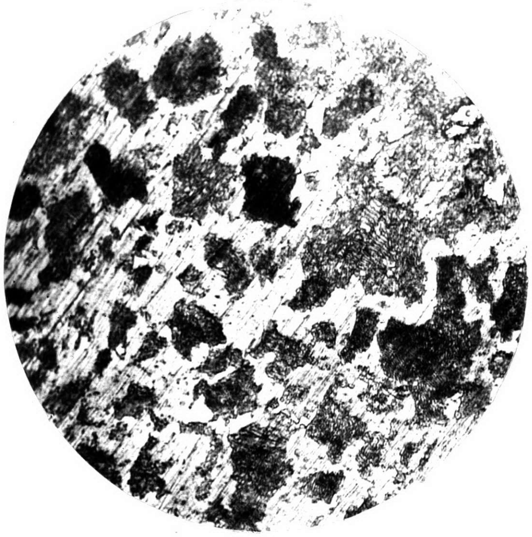

.45 % C Patented
Before Drawing
CVI: Patented again after 6th draft
CVIII " " " 8th "
CIX " " " 9th "
CX " " " 10th "
CVI
CVIII
CX
CIX
Torsion /100 Diameters
Percentage of Overall Reduction
50
40
30
20
10
0
60
70
80
90
100


.45% C Steel Wire
No Intermediate Heat Treatment
Annealed Before Drawing
Patented " "
Tensile Strength lbs/sq in
Torsion 100 Diameters
% Elongation
Torsion
Tensile Strength
Elongation
200,000
150,000
100,000
50
40
30
20
6
4
2
0
0
20
40
60
80
100



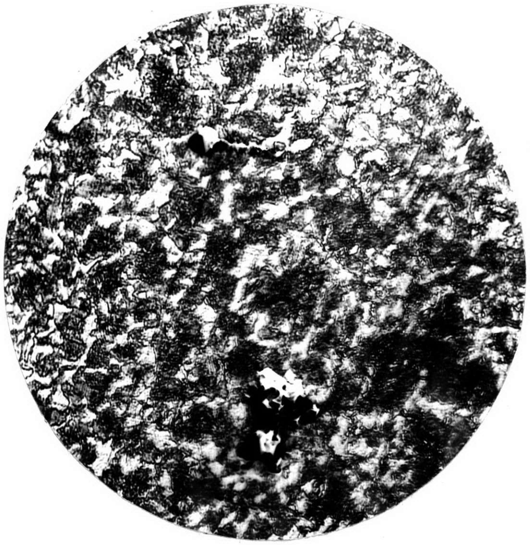
(1) A_0 .10% C., annealed at 1600° F

Longitudinal Section 250 X



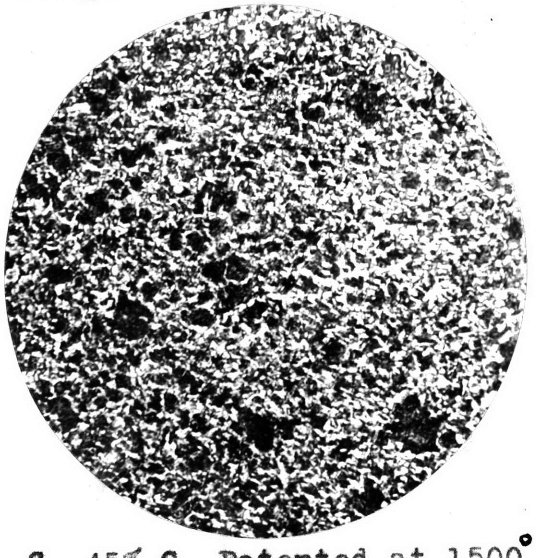
(2) B_0 .45% C., annealed at 1500° F

Longitudinal Section 500 X



(3) C_0 .45% C., Patented at 1500° F

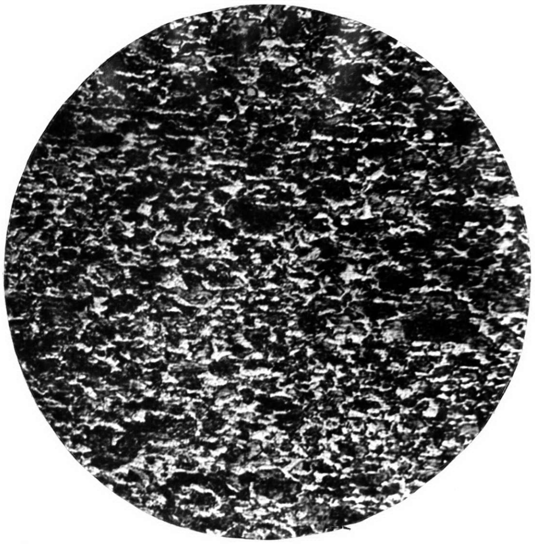
Longitudinal Section 500 X



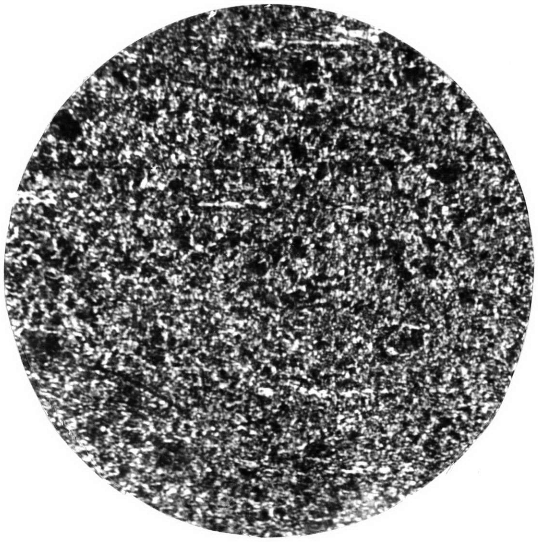
(4) C_1 .45% C., Patented at 1500° F

Cross secton 250 X

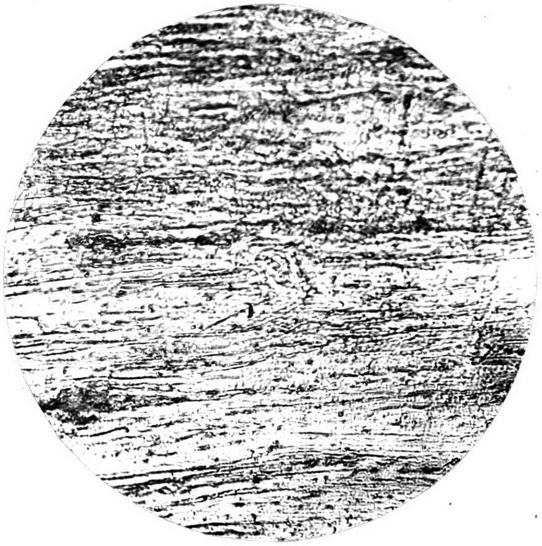
(After 1st. draft)



(5) C_1 .45% C., Patented at 1500°F
First draft ~~after intermediate~~
~~Patenting~~, long. section 250 X



(6) C_9 .45% C., Patented at 1500°F
passed through 9th. draft.
Cross section 250 X



(7) A_{10} .10% C., Annealed at 1600° F
After passing through 10th. draft
longitudinal section 500 X

(8) BX_5 .45% C., Patented at 1500 F
After passing through 5th. draft
Longitudinal section 500 X

Discussions

Plot 1--0.10% C.,annealed before drawing, (without intermediate heat-treatment). The tensile strength curve shows that from 0 to 45% reduction, the tensile strength increases by an amount of 23,000 pounds per square inch, at a uniform rate. After that the rate of increase accelerates and after about 85% reduction the acceleration is very rapid. In other words, after 85% reduction, a little amount of cold work will increase the tensile strength enormously. Hence the range of cold work from 85% reduction on is most effective for increasing the tensile strength.

The elongation curve shows that the drop in elongation is very rapid at first, but after about 45% reduction the rate of decrease diminishes.

The torsion is supposed to be a measure of ductility. Hence, we naturalyy expect it drops as the amount of cold work increases. But the torsion curve shows that, instead of this being the case, from 0 to about 40% reduction it increases slightly, before it begins to drop. The same phenomenon is seen in plot 8 for 0.45% C, annealed before drawing. This peculiarity may be explained as follows:-

The torsion at any point is the resultant of two factors:- The increase in brittleness tends to decrease it while the "skin effect", or skin tension on the circumfernce of the wire, produced by sqeezing the wire against the walls of the die, tends to increase it by preventing shear to take place at the circumference. We are all familiar with the surface tension of water, which will make a needle ~~to~~ float on its susface. The "skin effect", probably, re-enforce the circumference in a similar way.

Right after annealing, the brittleness factor is only at its minimum ; hence we get a pretty high value for torsion. After reducing the wire to about 45%, the brittleness factor increases, but, at the same time, the "skin effect" also becomes a factor in determining the torsion. This being the first draft, it is quite conceivable that the "skin effect" in this case is more effective than in the later drafts. The skin effect counter-balances the increase in brittleness. and, as a result, the torsion increases instead of decreasing, This explanation is supported by the following little experiment:-

We polish off the skin of two other samples of B_1 for about 2" in length and test them for torsion, which comes out to be 37 and 38 respectively, the break takes place in both cases at the polished portion. The difference in diameter between the original and the polished portion is made very small so that it will not affect the torsion appreciably.

Comparing the average torsion value of 37.5 with 54 for the original value, the effect of the skin on the torsion is evident.

In the torsion curve in plot 15, we do not have any such peak as in plot 1 or plot 8. This may be due to that after patenting the grains are not so soft as after annealing. Hence, the draft does not produce as great "skin effect" as after annealing. As a result, the "skin effect" in this case is not great enough to counter-balance the increase in brittleness.

Plot 3 is made ot answer such a question as follows:-

Given a rod of about .110" in diameter, we are required to reduce it to a wire of .028" in diameter. The dies available are assumed to be limited/ The problem is : At which draft we should anneal the wire in order to secure the best results in tensile strength, elongation, and torsion.

Plot 3 shows that AVIII gives greater tensile strength than AX orAIX at the size ofthe fisinished wire. This is what we should expect, since the treat-ment for AVIII gives the wire more drafts after annealing than AX or AIX. Plot 6 shows that the percentage of elongation given by AVIIII compares favorably with AX or AIX, too. Pot 7 shows that the torsion for AVIII is too low, being only 2.5. Comparing plots 3, 6, and 7, it is evident that the gain in tensile strength of AVIII is not great enough to offset its loss in torsion. Hence considering everything, the treatment for AIX or A AX is better than that for AVIII.

If we want to reduce the wire to another size, say .030", instead of .028", we can determine in a similar way which of the three heat-treatment is most desirable. If we rate tensile strength, torsion, and elongation with definite ratios, or if we fix lower limits for torsion and elongation, we can reach more definite conclusion as to which of the three methods is the best.

Plot 2 is a combination of tensile strength and torsion cuvres in plot 1. It combines two of the most important properties in a wire and presents to the reader more vividly as to which draft is more desirable and which not. For instance, the first draft is very desirable, since, both tensile strength and torsion increases, while the second draft is so desirable, since it reduces the torsion a great deal but increases the tensile strength not much.

Plot 4 shows the effect of cold work upon tensile strength, after the wire has been sujected to severe cold work and then fully annealed. By comparing it with the tensile strength curve in plot 1 we see that : (1) The tensile strength for no reduction is almost the same in both cases and (2) the rate of increase in tensile strength is nearly the same. These two points are better confirmed in plots 8 and 11. This means that annealing relieves all the cold work, which is, of course, in confirmity with the accepted theory of heat-treatment.

Plot 6 shows that the percentage of elongation drops very rapidly after the first draft and much more slowly afterwards.

Plot 11, reveiwing the curves as a whole, shows that the effect of previous cold work has all disappeared after annealing. It is interesting to note that the effect of cold work on tensile strength seems to be the same , no matter at which draft the wire is annealed, because all the curves nearly coincide.

Plot 12-- The general tendency of all the curves is about the same. If the experiment could be carried far enough, definite relation might be set up between tensile strength and torsion.

Plot 14--According to the stage at which the heat-treatment is applied, torsion curves should be in the order of BX, BVIII, BVII, and BVI, each higher than the other, because of the less amount of reduction after intermediate annealing . In the plot, however,BVII and BVIII are above BX. If intermediate annealing is applied after the seventh draft, a higher torsion value can be obtained without decreasing its tensile strength much (see plot 10). So far as the torsion is concerned, BVII is t the best.

Plot 15--In the tensile strength curve the rate of increase is uniform up to about 62% reduction at 1,000 pounds per square inch for every 1% reduction . Then its rate of increase is higher from 62% reduction on. After 90% reduction, tensile strength increases tremenduosly with very slight reduction. For instance, if we reduce the wire from 90 to 93% , the increase of tensile strength is about 36,000 pounds per square inch for every 1% reduction. The torsion curve decreases gradually with increase in percentage of reduction, while the elongation curve drops down quite rapidly up to 20% reduction.

Plot 16-- The tensile strength decreases with increase in torsion. When compared with plot 9, it shows that the ~~tensile~~ ~~strength~~ of annealed wire is more ductile than patented.

Plot 17--The most interesting fact here is that the tensile strength of CVI increases up to a certain point and then drops down suddenly. That is to say, sometimes a wire when patented at one particular stage cannot be drawn beyond a certain draft, or in other words, the grains are so elongated that , when drawn further , they suffer a breakdown in their internal structure. If it is to be drawn any further without injury to its physical properties, it is necessary to have it patented once more before it comes to the critical point. In other words, if the ~~draft~~ last draft is the desired size of wire, it is patented too early. This is shown by the fact that no such defect occurs in CVIII, CIX, and CX curves. The tensile strength for CX, however, is rather low at the finished wire.

Plot 20--The elongation curves are practically the same to those given by the annealed wires except that, at the initial stage before drawing, the elongation after annealing is much higher than after patenting. The difference is due to the process of heat-treatment. Of course the material is more ductile when annealed because of its pearlitic structure, than when patented, because of its sorbitic ~~str~~ structure. It is rather doubtful whether the value of elongation for CVI and for CIX should be slightly increased at the last drafts.

Plot 18--CVI begins to raise rapidly at about 40% and CVIII, at about 70%; while CIX seems not to change its slop very much even at about 80% of reduction. Keeping in mind that the magnitude of the cross sections of the wire after intermediate annealing are in the order of CVI, CVIII, and CIX, these curves seem to indicate that in subject-a wire of bigger diameter and one of smaller diameter to the same amonnt of cold work, the point where the th tensile strength begins to increase rapidly occurs in the bigger wire earlier than in the smaller wire .

From experience, we know that we can have heavier draft in smaller wires than in bigger ones. Looking from another angle, we might expect that if we subject two wires of different diameters to the same seies of reduction, the bigger wire will reach the point where the tensile strength begins to increase rapidly earlier than the smaller one. This is just what the curves show.

The curve for CVI has some peculiarity, The tensile strength reaches a maximum somewhere between 53% and 60% of reduction and with further reduction, the tensile strength, instead of increasing, decreases rapidly. The wire is said to be overdrawn. The ratio of tension and compression, exerted by the die, is too big. There is some incipient rupture and the density will actuaely decrease.

Plot 19--In plot 19 as in plot 12, the various curves, with the exception of CVI, are very close together, which suggests that we migtht draw a single line, or rather curve, of tensile strength against torsion for all of them. This is very interesting and means that when the draft is more or less the same, we get a definite relayion between tensile strength and torsion independent of the sizes of the wire.

CVI deviates a great deal from the rest, due to being overdrawn, as explained in connection with plot 18.

Plot 21--With two exceptionally low values of torsion at the start, the general nature of the torsion is decreasing with increasing in reduction.

Plot 22-- This plot gives the comparison between annealing and patenting for .45% C. steel wire. As we may expect, the tensile strength is higher throughout in the case of patenting than of annealing, while torsion and elongation are lower. One important point to note is that patenting treatment makes possible further drawing than annealing. The annealed sample breaks at about 85%, while the patented does not until about 93% of reduction. This is interesting, for we usually think that as the sorbitic structure is not so soft as the pearlitic, it will sustain less drawing.

The torsion for the annealed has a peak, while that for the patented none. This has already been discussed in connection with plot 1.

In all the curves of tensile strength against reduction of area, we have a proportionality between the tensile strength and the reduction, until a critical point is reached, after which point the tensile strength increases more and more rapidly.

Photomicrographs--The long annealing process shows the crystals evenly arranged and the whole steel of a uniform nature.(See photomicrographs 1 and 2) At the first pass of the patented specimen ~~the~~ (photomicrograph 5) , the crystals are beginning to assume a longitudinal direction. In photomicrographs 7 and 8 the fibre of the steel is very much elongated and at this point there must be a greater strain internally, so much so that it does not take much to make it show indications of fracture.

Conclusions

From the discussion above, we may draw the following general conclusions :-

(1) That the low carbon steel wire can stand heavier drafts than the medium or high carbon steel wires.

(2) That there is a proportionality between the tensile strength and the percentage of reduction of area, until a critical point is reached, after which point the tensile strength increases more and more rapidly.

(3) That, generally, torsion decreases with increase in cold work, but, sometimes, due to the "skin effect", it increases after the first or the second draft and then drops down.

(4) That the effect of cold work upon tensile strength is almost the same, no matter at which draft the intermediate heat-treatment is applied.

(5) That the best stage for intermediate heat-treatment is usually not at the breaking point, but at one, two, or three drafts earlier, depending upon the desired size of the finished wire.

(6) That there seems to be some definite relation between tensile strength and torsion, inde-

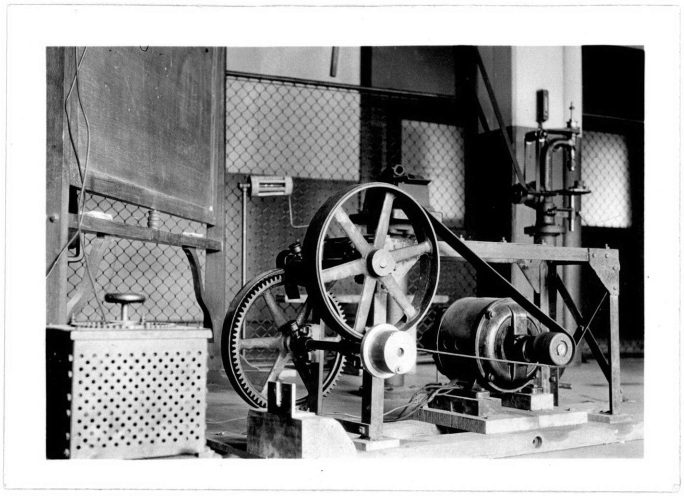
pendent of the different sizes of the wire and the particular draft for intermediate heat-treatment.

(7) That the patenting process permits more cold work than the annealing process.

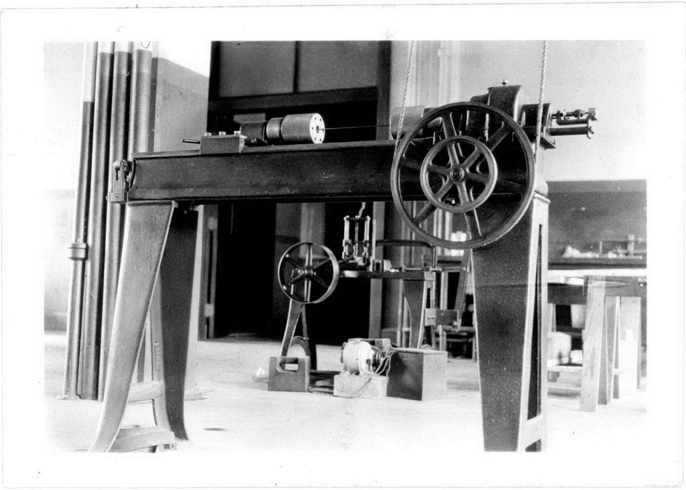
(8) That with the same amount of cold work, a patented wire has higher tensile strength and an annealed one has greater ductility.

(9) That there is a dritical point beyond which the wire will be overdrawn and ruined.

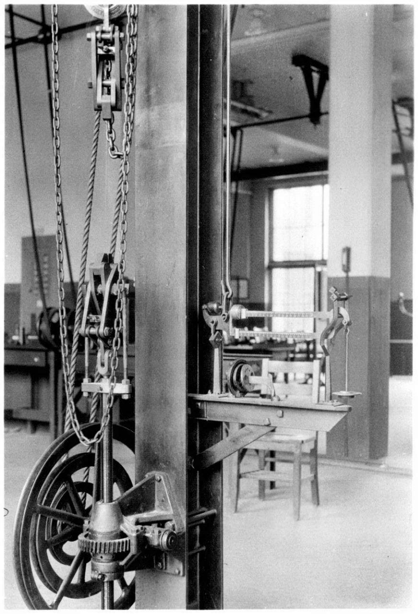
The End.



Drawing Frame



Torsion Test Machine



Tension Test Machine