METALLOGRAPHIC AND PHYSICAL PROPERTIES OF SOME COLD DRAWN WIRES

by

CLIFFORD WARREN WHEELOCK

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APPROVED:

[redacted]

Professor of Mechanical Engineering
In Charge of Major

[redacted]

Head of Department of Mechanical Engineering

[redacted]

Chairman of School Graduate Committee

[redacted]

Dean of Graduate School

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INTRODUCTION

In general, wire is a term that may be applied to any metallic shred, thread, or filament, or to any exceedingly slender rod or bar of metal having a uniform cross section. Considering the term in this sense, wire is of very ancient origin. Gold wire is mentioned in the Bible in connection with the sacerdotal robes of Aaron, and was used to form part of a necklace found at Denderah, which bears the name of the Pharaoh who reigned in Egypt about 2750 BC. Evidences of the use of wire by the Assyrians and Babylonians as far back as 1700 BC have also been found. As to the methods of manufacture used by these ancient peoples, practically nothing is known. The specimens of ancient wire, that have been found so far, are flat, and it is probable that they were produced solely by hammering.

How, when, or of what material round wire was first made is not known. No doubt it was first produced by hammering, but the difficulty of forming a fine round wire by this method probably caused the metalworkers, early in the history of the art, to seek some better method. An old Latin manuscript written by Theophilus sometime during the eighth or ninth century describes a method of making wire of an alloy of lead and tin which was cast into an ingot, hammered into a long slender bar and drawn through holes in a wire-drawing plate. The draw plate itself, is described as "a piece of iron three or four fingers wide, smaller at the top than at the bottom, rather thin and pierced with three or four rows of holes through which wire may be drawn." However, there is reason to believe that the art of wire drawing was known and practiced before this time. The chain armor used by the knights in the great crusades against the Saracens and Turks is thought by many to have been made of drawn wire.

Other authentic records are available to show that wire drawing on a commercial scale was practiced in France in 1270, in Germany in 1350, and in England in 1465. The first wire-drawing mill in this country was built by Nathaniel Miles at Norwich, Connecticut. Although three other mills, two of which were in Pennsylvania, were started during the next twenty years, none of these appears to have been very prosperous, for in 1820 practically no wire was being made in this country. In 1831, however, the industry was re-established by Ichabod Washburn of Worchester, Massachusetts, who, with Benjamin Goddard, founded the firm of Washburn, Moen and Company.

About 1650, in Germany, steel was first drawn into wire after many years of fruitless effort by a process, discovered quite by accident, using urine to catalyze the formation of the iron hydrate sull coating necessary to lubricate the steel in the die. Since that time, water, acid, and electrolytic deposits of tin, copper, or alloys of the two have been found to be more suitable than urine, and wire has become so common that today practically every industry makes use of wire in some way. The present production of wire represents about one-twelfth of all the steel produced in the country, and if it were all drawn into No. 16 wire, which is about the average gage, it would have a total length of more than 122,000,000 miles, or enough to girdle this earth about 4912 times (5, p 1066).

PROCESSES AND OPERATIONS

The shapes and sizes into which wire is drawn include cross sections of practically any geometrical form desired, ranging in size from less than one thousandth of an inch to four or more inches in diameter.

The original drawing benches were of the single-draft type which are used today for special jobs, but as the length of a strand so drawn could be no longer than the bench, continuous processes were rapidly developed after the Industrial Revolution, particularly in this country. The continuous process for most types of wire starts with five gage rolled rod which has been properly prepared for drawing and wound on a reel to several hundred pounds; numerous reels being welded together if a very long continuous strand is desired. From the reels the rod passes through the lubricant or liquor in the die box, through the die, around a block two or three turns and on to the next die, die box, and block; the process continuing, possibly passing through an annealing furnace between dies, until the desired size has been obtained in which case the wire is wound in convenient bundles or on reels; or until the speed required to continue pulling the wire, which has become several times its original length, becomes impractical. The maximum allowable drawing speed depends upon the nature of the material, its size, shape, and type of machine used, varying from about ten feet per minute for thick bars of mild steel from two to four inches in diameter to one thousand feet per minute in drawing fine copper wire (1, p 45).

DIES

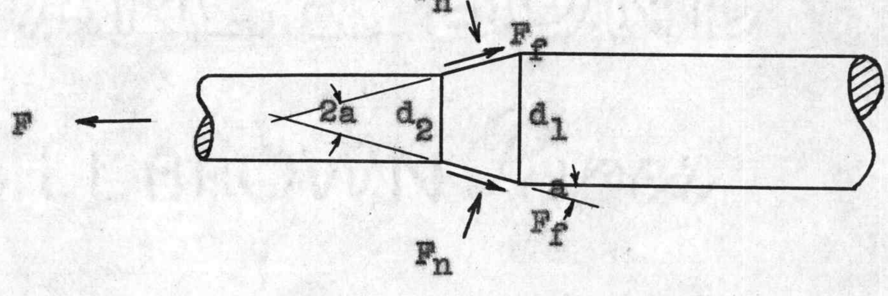
There are two distinct classes of dies; those of malleable metal which can be reset either hot or cold, and those of hard unworkable metal which cannot be reset.

The main properties of the former are low cost and excellent lubricating qualities, but their life is short. The hard dies, including principally chilled cast iron and in more recent times tungsten carbide, hold their size longer than malleable dies; however, they cannot be reset, but must be enlarged to the next size if used again.

For drawing very fine wire, diamond dies in which the holes are made by electric spark are frequently used.

Some manufacturers practice tilting the die from the line of the entering and leaving wire by as much as six to twelve degrees to induce a specific set in the wire causing it to coil naturally to the diameter of the desired bundle. They thereby reduce snarling if the wire should break or the machine jam. This practice, however, tends to produce flat wire which, though acceptable for some purposes, is not usually desirable.

As a measure of the pressures to which the die is subjected, the following derivation is useful:



The sum of the forces resisting the pulling force, F, must be equal to F,

$$F = F_f \cos a + F_n \sin a$$

$$= F_n(f \cos a + \sin a)$$

$$F_n = \frac{F}{f \cos a + \sin a}$$

$$P = \frac{F_n}{A} = \frac{F_n}{\frac{\pi}{2}(d_1 + d_2)\frac{(d_1 - d_2)}{2 \sin a}}$$

$$= \frac{F}{(f \cos a + \sin a) \frac{\pi}{4 \sin a} (d_1^2 - d_2^2)}$$

$$P = \frac{F}{(f \operatorname{ctn} a + 1)(A_1 - A_2)}$$

Where

F = Drawing pull, lb

d_1 = Wire diameter before draw, in.

d_2 = Wire diameter after draw, in.

A_1 = Wire area before draw, sq in.

A_2 = Wire area after draw, sq in.

$2a$ = Approach angle of the die

f = Coefficient of friction

P = Unit pressure on die, lb per sq in.

LUBRICANTS

The greatest problem in wire drawing is the maintaining of a lubricating film between the wire and the die. As the pressures involved usually exceed 60,000 pounds per square inch in drawing steel wire, common fats and mineral oils that form films which break down at about 5000 pounds per square inch are of little use. It has been established by practice and research that the most efficient lubrication is obtained with dry soap (1, p 46) and for commercial dry drawing, a soap-lime-hydroxide film forms the lubricant. This coating is usually applied by pickling the rod to be drawn in acid to remove dirt and scale, and hanging it in a damp place to rust. When this newly formed rust becomes a greenish-brown, the rod is put into a boiling solution of lime after which the rust-lime coated rods are baked for several hours at 250 to 500 F which removes any moisture and also any hydrogen which may have been adsorbed in the acid pickling process, the presence of which may cause brittleness. The soap is added to this coating as the wire passes through the die box. Other lubricating materials such as meal, tallow compounds, graphite, etc are also often used with good results but in any case the acid, lime treatment is almost universal in dry drawing practice.

The other commercial drawing process, known as wet, liquor, electrolytic, or bright drawing, in effect draws a cylinder of soft metal with a steel core. In this process, the cleaned rods are placed in a solution of copper sulfate and a salt of copper and/or tin which deposits a very thin coating on the steel. This plating remains on the drawn product forming a bright finish of the deposited metal, but is not particularly effective in reducing corrosion as the finish might misleadingly indicate.

RAW MATERIAL

The steel for wire is produced by all the modern processes. Some special grades of wire are still made from Swedish wrought iron, but crucible steel is now seldom, if ever, used (5, p 1069). Instead of these high-priced products, plain carbon steels produced by the basic open hearth, acid open hearth, or bessemer processes have been successfully substituted, leaving only certain high alloy steels that are made in electric furnaces.

Although the bulk of the wire produced is of low carbon content, certain uses such as springs, musical instrument strings, and the like demand a stronger product which cannot be obtained by cold work on low carbon steel. This has led to the drawing of high carbon and alloy wires, some of which, in the form of piano wire, have attained tensile strengths of 400,000 pounds per square inch or more.

The selection of steel for such high strength products often becomes very critical, especially since the higher carbon steels are frequently quite dirty, and even inclusions which flow readily in soft steels, may be the source of seams or cupping which would prevent appreciable drawing in high carbon specimens. This condition can be overcome to some extent, however, by proper heat treatment.

HEAT TREATMENT

The heat-treating processes used in the wire industry are known as annealing, patenting, and hardening and tempering. Of these patenting may be described as a special toughening process used only in the wire industry, while annealing, hardening, and tempering play an important part in many industries.

Of the three heat treatments mentioned above, annealing is the most common, and to the soft, or low carbon, steel wires which constitute by far the largest tonnages, it is practically the only heat treatment given. In general, the process is employed in the wire industry to accomplish any of three objects; to refine or make uniform the grain structure of rods or wire, to obtain a definite structure in, and thus impart special properties to the finished material, and to soften the wire after cold working such as drawing or rolling.

Just as the carbon content sets the initial level upon which added strength is built by cold working, so the initial structure in a steel of given carbon content sets its initial strength level and effects the response to cold work. Patenting, a preliminary heat treatment from above the critical, is therefore often applied prior to cold working, especially for cold drawn piano wire, and, in larger sizes, for suspension bridge cables. In patenting the austenite is first coarsened and thus made more sluggish by heating to a high temperature, and then either air cooled, or preferably quenched into a bath of molten lead held at a desired temperature not very far below the critical, in order to facilitate transformation to fine pearlite. This is an early use of the process now called austempering. The fine pearlite structure is stronger than a coarser one, and the final drawn product has greater strength than if the cold work were applied to a coarser structure (4, p 245).

Patenting under some conditions produces a sorbite structure in which the grains are very small and the iron carbide is distributed in very finely divided form in the ferrite (5, p 1125). The distinction between sorbite and fine pearlite offers some speculation, and it is proposed by many that a lamellar structure such as pearlite, no matter how fine, is not desirable for drawing (1, p 66). For hypoeutectoid steels it would seem probable that the patented structure is fine pearlite; however, the presence of iron carbide in spherical form rather than as cementite would be necessary if any degree of ductility were obtained in hypereutectoid steels.

RESULTS OF WIRE DRAWING

Cold drawing, like cold rolling or other methods of cold working, invariably increases the hardness, stiffness, tensile strength, and elastic limit, and at the same time, decreases the ductility and to a slight extent the electrical conductivity of the metal. This statement applies to copper and other metals as well as to steel. The extent of the changes of these properties is not always directly proportional to the amount of cold work done upon the metal, as it is affected by various factors such as total measure of drafting, number of drafts by which this total is reached, and the nature of the material itself. However, the wire drawers have determined from long experience what the total effect is for a great many different sets of conditions, so that if the conditions of manufacture are known, the physical properties of the finished wire can be estimated with a fair degree of accuracy.

The wire drawing process accomplishes one or more of the following results:

1. By this process metals are elongated and reduced in section to an extent not attainable by any other method.

2. By this process a greater degree of accuracy as to size and section can be attained than is possible by any other method except cold rolling which is not applicable to common sizes of wire or to fine wire.

3. The process is capable of producing a uniformly smooth and highly polished surface.

4. The process serves as a more or less sure test for the detection of hidden flaws in the metal. The fact that a wire has satisfactorily withstood the drawing operation may be taken as a reliable indication that the metal was originally sound and free from defects liable to cause failure in service. This does not mean that the wire itself is free from defects, for it is possible to produce certain flaws by improper drawing.

5. Finally, the process affects the physical properties of the metal, which makes it possible in conjunction with heat treatment, to produce many wires having different mechanical properties from the same steel.

TEST EQUIPMENT

Among the equipment used in wire drawing, the most important element is the die; the unit which has determined the success or failure of most wire industries. The dies used for this study were Carboloy cemented carbide dies made by the Carboloy Company, Inc, manufacturers of numerous drawing, stamping, and pressing dies. The production of these dies involves forging a steel case around the carbide core, drilling, grinding, and polishing to obtain the hole size and shape required to 0.0001 inch tolerances, and finally polishing with No. 6 diamond dust on a cotton and toothpick swab (6, p 11).

Two sets of dies were used, designated below by die diameters in inches, those on the left having an outside diameter of one and one-half inches, and those on the right of one inch.

0.164	0.0475
0.140	0.0410
0.120	0.0345
0.102	0.0317
0.087	0.0285
0.073	0.0260
0.061	
0.0508	

The wire drawing bench used, shown in Figure 1, consisted of a screw ten feet long which was advanced by a rotating nut held from lateral movement by two bearings, one on each side of the nut. The assembly was mounted on a steel bench with guides so that the screw could advance but would not rotate as the nut was turned. A one horsepower direct current motor was mounted to drive the nut by

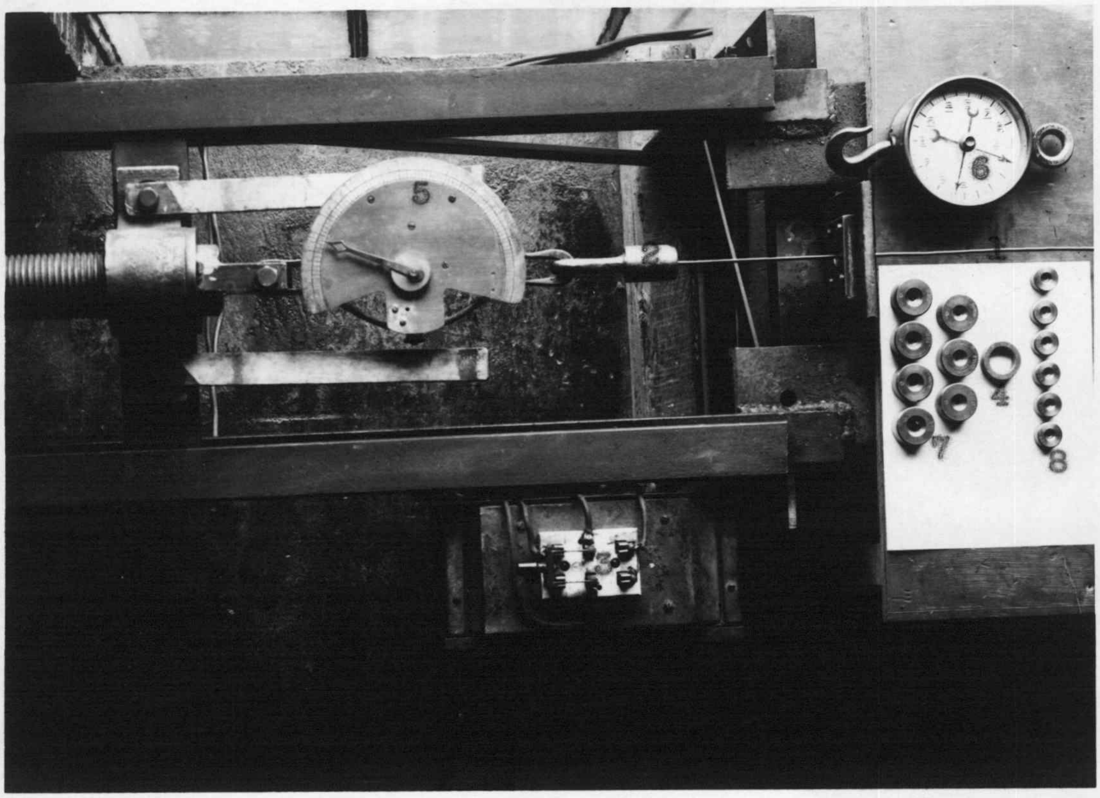


Figure 1. Top View of Drawing Bench.

(1) The wire being drawn.

(2) The chuck for gripping the wire.

(3) The reversing switch for the drive motor.

(4) The guide used to center the small dies.

(5) The 2000-pound capacity traction dynamometer.

(6) The 200-pound capacity traction dynamometer.

(7) The large dies, from 0.164 to 0.0508 in.

(8) The small dies, from 0.0475 to 0.0260 in.

a chain and sprocket drive; the motor drawing current at 40 to 50 volts from a 1200 rpm high output generator driven through a flat belt by a 7.5 horsepower three-phase alternating current motor. A stationary die holder held the 1-1/2 inch diameter die in place while the wire, held by a grip consisting of a taper-bored sleeve with sliding tapered jaws and a hook threaded into the sleeve, was connected to the screw through a traction dynamometer and clevis. When the small dies having an outside diameter of one inch were used, the centering guide, (4) Figure 1, was required.

Two dynamometers were used; (5) Figure 1, one of 2000-pound capacity for the larger wires which required a drawing pull greater than 200 pounds, and (6) Figure 1, a Schaffer & Budenberg dynamometer of 200-pound capacity for small wires.

The machine used for tensile testing the drawn specimens was a Tinius Olsen 30,000-pound, gear-driven testing machine, Figure 2, using a small rider of one-tenth of the rating, making each scale division a half-pound increment.

The extensometer, upper left, Figure 2, was a two-inch Tinius Olsen Model S-3 with 0.0001 inch graduations.

For measuring hardness, the Tukon Micro-Hardness tester, manufactured by the Wilson Mechanical Instrument Company, Figure 3, was used to measure 136-degree Diamond

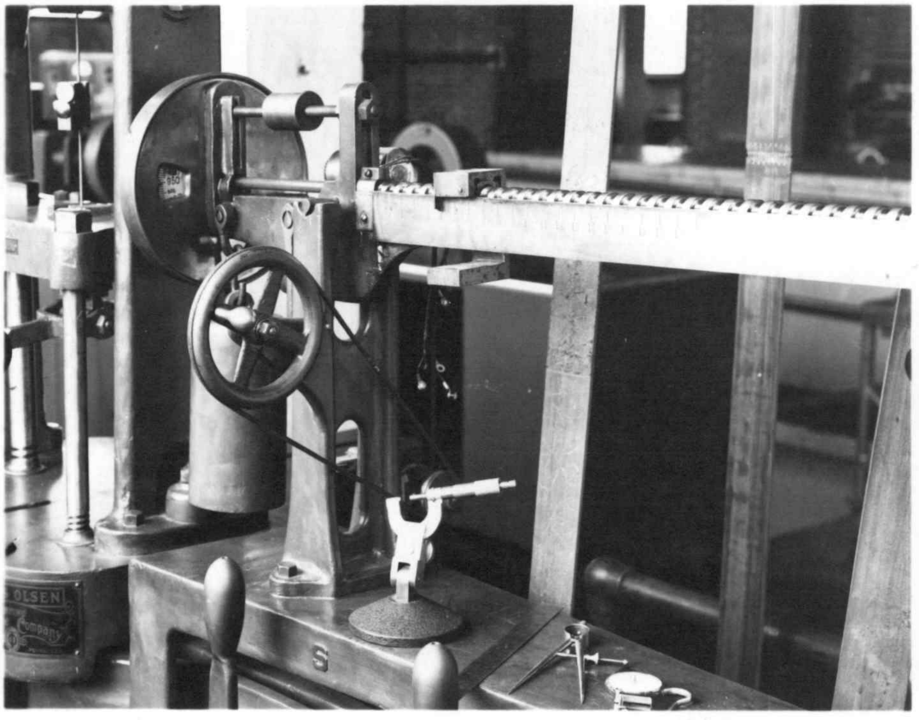


Figure 2. Tinius Olsen 30,000-lb Testing Machine.

The extensometer is shown on a test specimen in the upper left corner.

Pyramid Hardness which corresponds closely to Brinell hardness in value, being determined by forcing a square base diamond pyramid having an apex angle of 136 degrees into the specimen under load and measuring the diagonals of the recovered indentations. The Diamond Pyramid Hardness is defined as the load per unit area of surface contact in kilograms per square millimeter, as calculated from the average diagonal as follows:

$$D\ P\ H = \frac{2\ L \sin \frac{a}{2}}{d^2}$$

Where

D P H = Diamond Pyramid Hardness

d = length of the average diagonal, mm

a = apex angle, 136 degrees

L = load in kilograms

The micrographs included in this paper were taken on the Leitz Metallograph, shown diagramatically in Figure 4, using a 16-millimeter apochromatic objective and 4X periplan eyepiece with a bellows setting of 39.5 cm and 81.0 cm for the 100- and 200-diameter magnifications respectively. For the 500-diameter micrographs a 4-millimeter apochromatic objective, a 4X periplan eyepiece, and 61.0 mm bellows setting were used.

Other necessary equipment included an electric heat treating furnace and salt bath in addition to grinding and

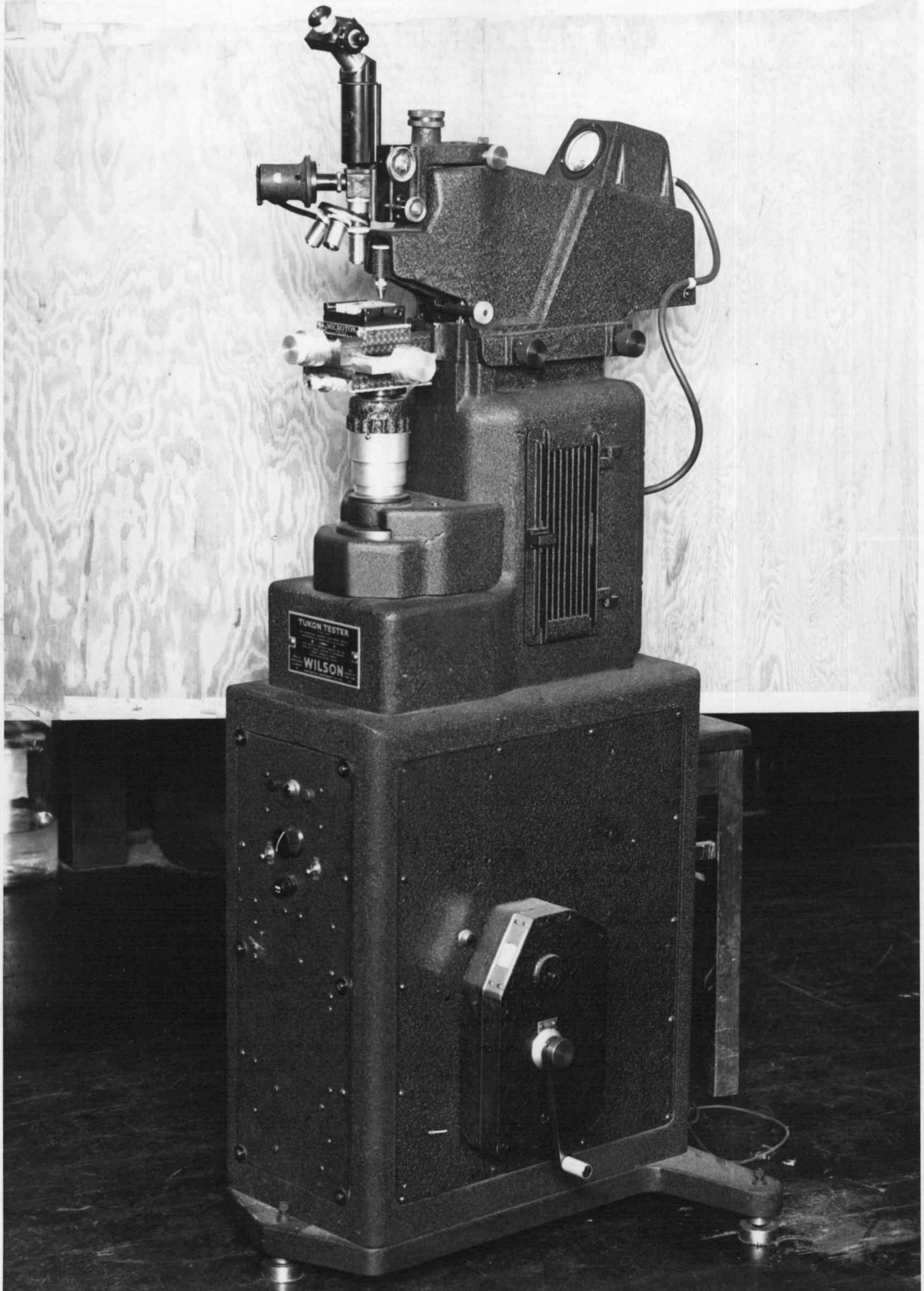


Figure 3. Tukon Micro-Hardness Tester.

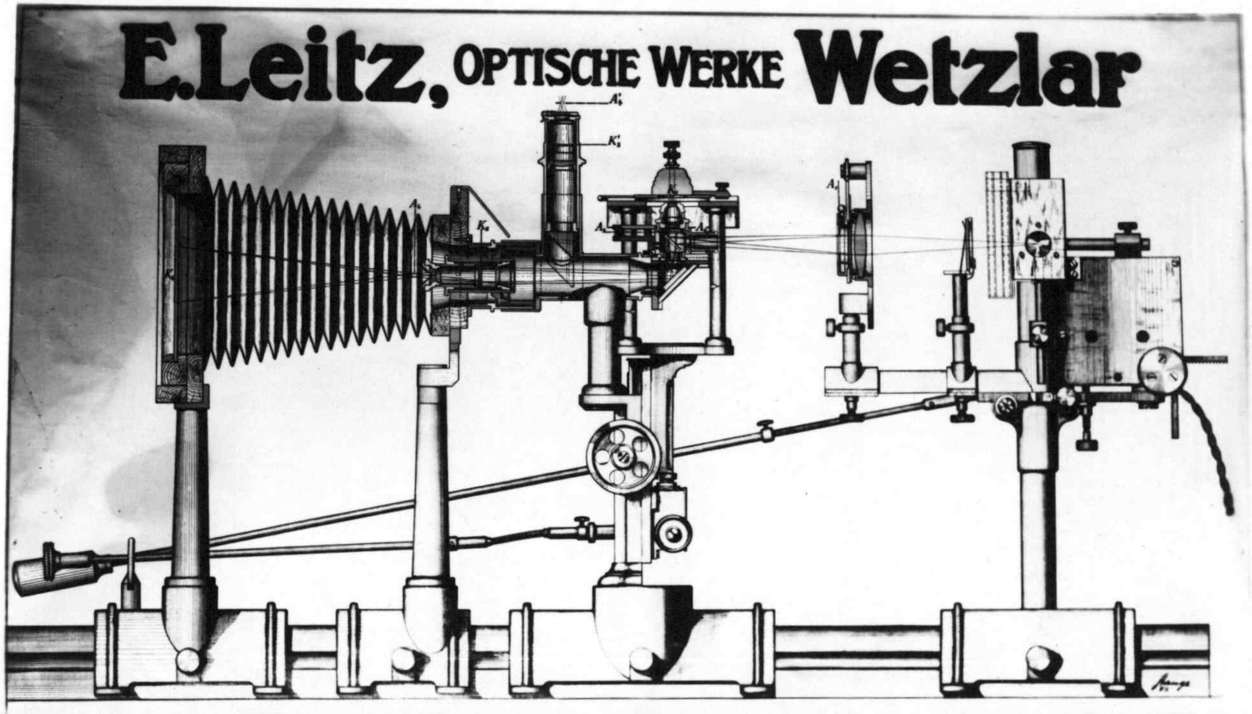


Figure 4. Leitz, Micro-Metallograph.

polishing equipment and various hand tools.

TEST SPECIMENS

Five different plain carbon steels were drawn and investigated, the standard analysis of which follows:

1. Common Soft Steel Wire, the source of which was unknown, but which appeared and was considered to contain about 0.1 percent carbon.
2. C-1019 Steel, 0.15 to 0.20 percent carbon, 0.70 to 1.00 percent manganese, 0.04 percent maximum phosphorus, 0.05 percent maximum sulfur, and 0.10 percent maximum silicon.
3. C-1065 Steel, 0.60 to 0.70 percent carbon, 0.60 to 0.90 percent manganese, 0.40 percemt maximum phosphorus, 0.05 percent maximum sulfur, and 0.10 to 0.20 percent silicon.
4. Columbia Standard Tool Steel, 1.00 percent carbon, 0.25 percent manganese, and 0.20 percent silicon.
5. C-1095 Steel, 0.90 to 1.05 percent carbon, 0.30 to 0.50 percent manganese, 0.04 percent maximum phosphorus, 0.05 percent maximum sulfur, and 0.15 to 0.30 percent silicon.

PROCEDURE

This project involved the preparation for drawing, drawing, tensile testing, hardness testing, and metallographic examination of the steels listed on the preceding page.

The specimens, as received, were straight lengths eight feet long. As there was no heat-treating equipment available which would handle them in this form, they were rolled into coils approximately five inches in diameter, and placed in an electric furnace at 1750 F where they were covered with graphite and carburizing compound to reduce surface decarburization. After twenty minutes at this temperature, the steels were quenched in a salt bath at 1150 F, at which temperature they were held for sixty minutes, after which they were removed and air cooled.

The next step, undoubtedly one of the most important to successful wire drawing, was the cleaning of the material to be drawn. The heat-treated specimens were placed in a hydrochloric acid solution, having a specific gravity of 1.06, for thirty minutes which removed the scale and other abrasive material from the surface. They were then rinsed with water and placed in a boiling solution of lime and water where they remained for thirty minutes, after which they were dried in a furnace for six hours at 220 F. The excess lime was then wiped off, and the more or less porous surface rubbed with molybdenum sulfide, a graphite-like powder, which together with water-soluble machine oil, served as the lubricant while drawing.

To start the draw, the end of the wire was filed to extend through the die by about two inches so that it could be gripped by the chucks for drawing. Other methods of pointing, such as peening and grinding were tried but were not as satisfactory as filing; however, swaging would have been the most desirable method had dies for that machine been available. Drawing proceeded at approximately five feet per minute, the drawing pull being read for each draw from the traction dynamometer which had previously been calibrated. From each drawn wire, a tensile specimen fourteen inches long was cut, marked off into a ten inch gage length as recommended by the American Society for Testing Materials, and tested with readings of load and extension in two inches recorded for load increments ranging from ten pounds to two hundred pounds depending upon the specimen under test. After fracture, the length of the specimen was measured as well as the diameter of the break, and from these values the percent elongation in ten inches and percent tensile reduction in area respectively were calculated and plotted on the curves which follow.

Further drafts and tests proceeded as above for the two low carbon steels until they had been drawn through the smallest die, 0.0260 inch diameter; a total of fourteen passes for the 0.1 percent carbon steel and fifteen passes for the C-1019 steel. Drawing did not proceed so smoothly for the higher carbon steels, however. The C-1065 steel consistently broke in the 0.102 die as did the C-1095 steel in the 0.120 die and the Columbia Tool Steel in the 0.140 die; enough was drawn through before the fracture in each case, however, for the tensile test and for mounting specimens. The typical type of break produced in the die is shown in Figure 5. The C-1065 and the C-1095 steels were then reheated to 1200 F, cleaned, and again prepared for drawing as described previously. Both softened specimens drew readily for several passes, but after approximately the same percent reduction in area as before, similar fractures occurred when drawing; the C-1065 breaking in the 0.0475 die and the C-1095 in the 0.087 die. As no material increase in physical properties was obtained by the softening and drawing over those produced before the first die breaks, attempts to further reduce the size of the specimens were not made.

Having completed drawing and tensile testing the original and drawn specimens, small segments of each were mounted in bakelite so that transverse and longitudinal

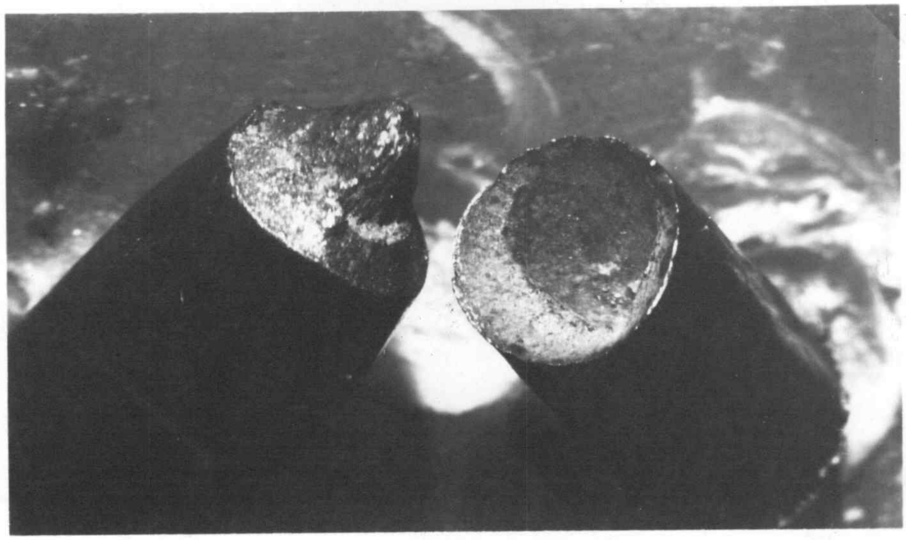


Figure 5. Typical Die Fracture, 10X

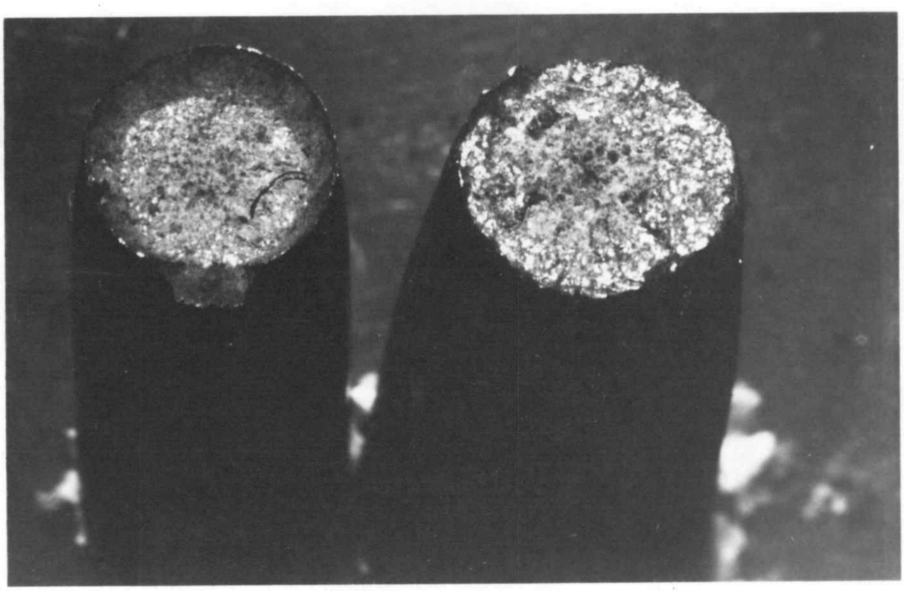


Figure 6. Typical High Carbon Tensile Fractures, 10X

Right - fracture of undrawn C-1095.
Left - fracture of same material after two drafts

sections could be studied. These were hardness tested for Diamond Pyramid Hardness on the Micro-Hardness tester after being ground and polished as for micrographic examination. Before etching, the polished specimens were examined at 100 diameters and some of the more interesting observations micrographed as shown, Figures 7 and 8. The micrographs which show the grain structures were taken at 200 and 500 diameters as indicated, after the various specimens were etched with 2 percent nital.

CALCULATIONS

The values which appear in the tables, I through XII, some of which form the source of the curves, Figures 9 through 15, were calculated as follows; the test values from the first draw of C-1019 steel, Tables II, VI, and X being used as samples:

Die Pressure, Tables V - VIII, from the formula as developed on pages 5 and 6.

$$P = \frac{F}{(f \text{ ctn } a + 1)(A_1 - A_2)}$$

$$2a = \text{die approach angle} = 12^\circ \quad (6, \text{p } 8)$$

$$f = 0.085 \quad (1, \text{p } 49)$$

$$P = \frac{F}{(0.085 \text{ ctn } 6^\circ + 1)(A_1 - A_2)} = \frac{0.553\ F}{A_1 - A_2}$$

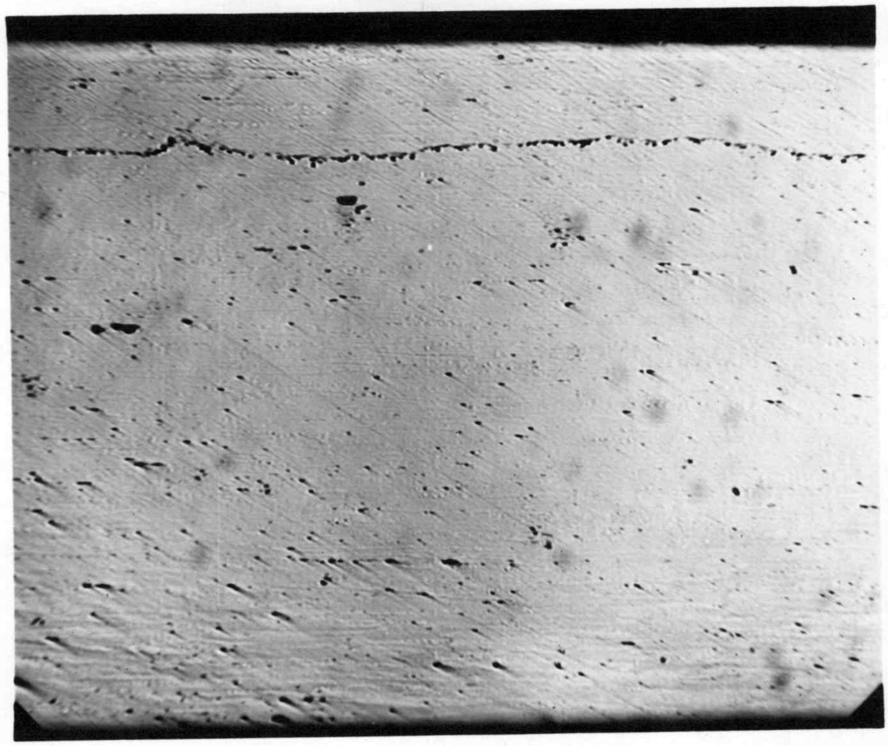


Figure 7. Separation in Drawn 0.1 Carbon Steel, 100X

Figure 8. Inclusions in C-1065 Steel, 100X

For drawing C-1019 from 0.1830 to 0.1635 in. diameter, a draw pull of 625 lb was required, Table II.

$$A_1 = 0.0263$$

$$A_2 = 0.0210$$

$$P = \frac{0.553 \times 625}{0.0263 - 0.0210} = \underline{65,300} \text{ psi}$$

136° Diamond Pyramid Hardness, Tables V - VIII. The average diagonal of impression produced by a ten kilogram load was measured in filar units using the 16-mm objective for which the calibrated multiplier to convert to millimeters was 0.0699. For the original sample of the C-1019 steel, the average impression diagonal was 4.61 filar units or

$$4.61 \times 0.0699 = 0.322 \text{ millimeters}$$

$$D\,P\,H = \frac{2\,L \sin \frac{a}{2}}{d^2} = \frac{2 \times 10 \times \sin 68°}{(0.322)^2}$$

$$= \underline{178} \text{ kg per sq mm}$$

The hardness values were not actually calculated for each case, as there was a table available which gave the hardness directly, knowing the average diagonal in millimeters.

Pulls per square inch of reduction in area, Tables V - VIII, measure the relative pulls required to draw the different samples, and show the same relative effect as the die pressure values since,

$$\text{Pull/sq in.} = \frac{F}{(A_1 - A_2)}$$

$$\text{Die Pressure} = \frac{0.553\ F}{(A_1 - A_2)}$$

therefore,

$$\text{Pull/sq in.} = 1.808 \times \text{Die Pressure}$$

or in the general case,

$$\text{Die Pressure} = \frac{\text{Pull/sq in.}}{(f \text{ ctn } a + 1)}$$

The other calculations required are simple and should readily be followed without elaboration.

DISCUSSION OF RESULTS

Obviously, cold working is capable of producing extremely great changes in the properties of a metal, and of the many methods of cold working, wire-drawing is capable of producing not only the greatest, but also the most uniform effects.

It would seem from the data that, for the softer steels, drawing could be continued almost indefinitely with a continued increase in the tensile strength and hardness, however, there were several indications that the limit to continued successful drawing, even of these low carbon steels, was approached. Figure 7 shows what appears to be a separation produced by extreme drawing of the 0.1 percent carbon specimen; however, considerable drawing beyond this point was successful, producing consistently increasing tensile strengths. This type of separation would appear to be, at least partially, the result of too great a reduction in area per pass, which would tend to produce a hollow cylinder of metal in which the grains were deformed by pulling on the inside while the surface was restrained, with a core deformed uniformly more as by a direct compressive force; the separation occurring at the junction of the two types of deformation. This type of effect was also indicated by the type of tensile fracture, Figure 6, produced for the higher carbon steels.

The undrawn specimens of all three high carbon steels produced square type tensile fractures, but the same materials after one or two drafts, consistently showed a shear type failure for the surface and a square type break at the center, Figure 6. It would seem, however, that had such non-uniform deformation taken place, it would have been detectable by metallographic examination, but no conclusive indication of such appeared to be present. On the other hand, in viewing a deformed granular structure, it would be almost impossible to determine whether a grain had been deformed by a simple compression or by a couple effect.

Figure 8 shows that the inclusions in the C-1065 steel were many and in some places constituted a definite part of the section of the wire. Inclusions of this sort, especially when on the surface, could conceivably be a source of drawing failures, and would reduce the tensile properties somewhat.

The increase in die pressure and drawing pull per square inch of reduction in area as the specimens were reduced by drawing, Figure 9, show a more or less linear relation up to about 80 percent reduction after which the increase was much more rapid, typical of an inverse proportionality relationship.

The die pressures produced in this test compare favorably with values obtained by other investigators. Lewis has experimentally determined the die pressure to be about 70,000 pounds per square inch for mild patented wire (1, p 49). The higher carbon wires after being softened following the die failure, both drew the first draft with a lower die pressure than the original wires, indicating some structure change, but following drafts produced a more rapid rate of increase than before heating.

Relations similar to those indicated above were found between ultimate strength and drawn reduction in area, and between hardness and reduction in area, Figures 14 and 15 respectively, except that the ultimate strength of the last two drawn specimens of C-1065 seemed to have a lower

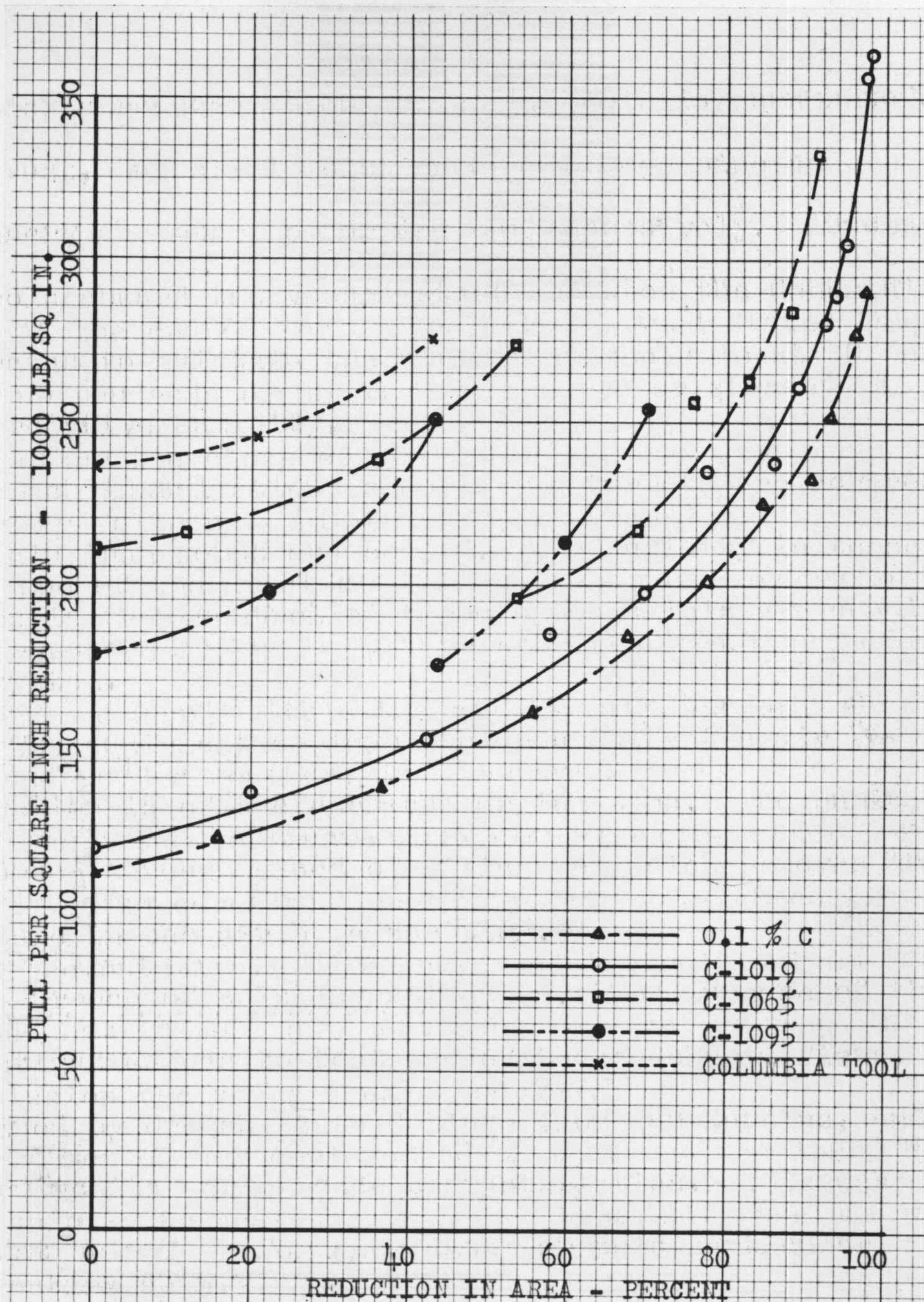


Figure 9. Variation of Drawing Pull per Square Inch with Drawn Reduction in Area for Five Carbon Steels

ultimate than that attained by some of the larger specimens of the same material. These specimens both broke in drawing, however, and the smaller one had two detectable "bumps" through which the wire broke with only a slight bending force. The tensile specimen did not include any of these sections. The "bumps" could have been a form of parabolic cupping (2, p 104), but such was not detectable under the microscope.

The stress-strain curves for the various steels before drawing, Figure 10, showed the steels to have yield points characteristic of ductile materials except for the Columbia Tool steel which had no definite yield but an increasing rate of elongation similar to that of hardened high carbon specimens and cast iron.

The elimination of a definite yield point in soft steel by cold drawing is indicated clearly by the stress-strain curves of Figure 11. Here all the drawn specimens of C-1019 steel retained the same modulus of elasticity, 28,850,000 pounds per square inch, but the elastic limit of the drawn specimens extended to considerably higher stresses than did that of the undrawn wire.

The two measures of ductility, elongation and tensile reduction in area, Figures 12 and 13 respectively, do not show exactly the same thing, though both indicate considerable reduction in ductility in all specimens as a

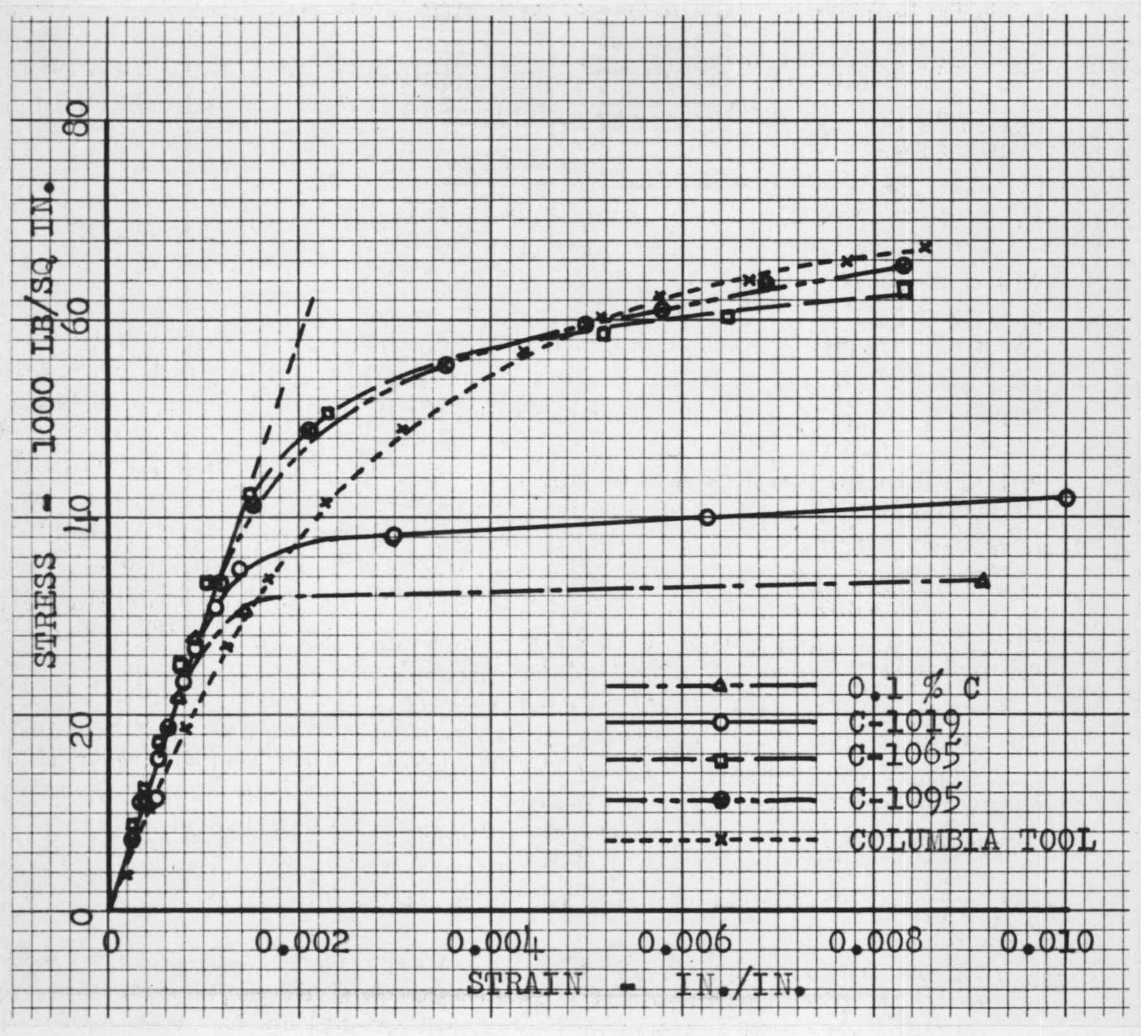


Figure 10. Stress-Strain Curves for Five Undrawn Carbon Steels

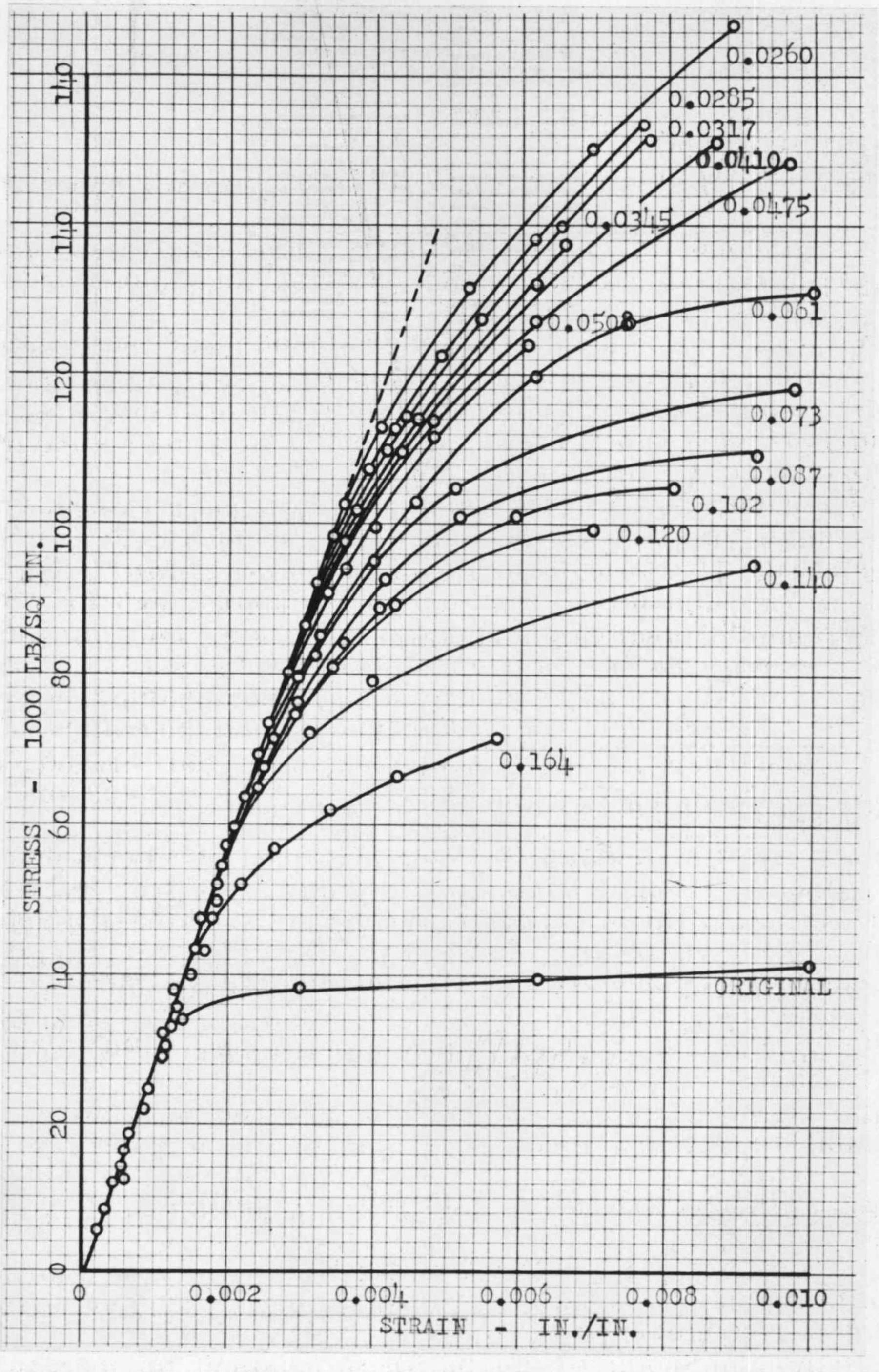


Figure 11. Stress-Strain Curve of C-1019 Steel Drawn Through Die Sizes indicated Without Intermediate Heat Treatment

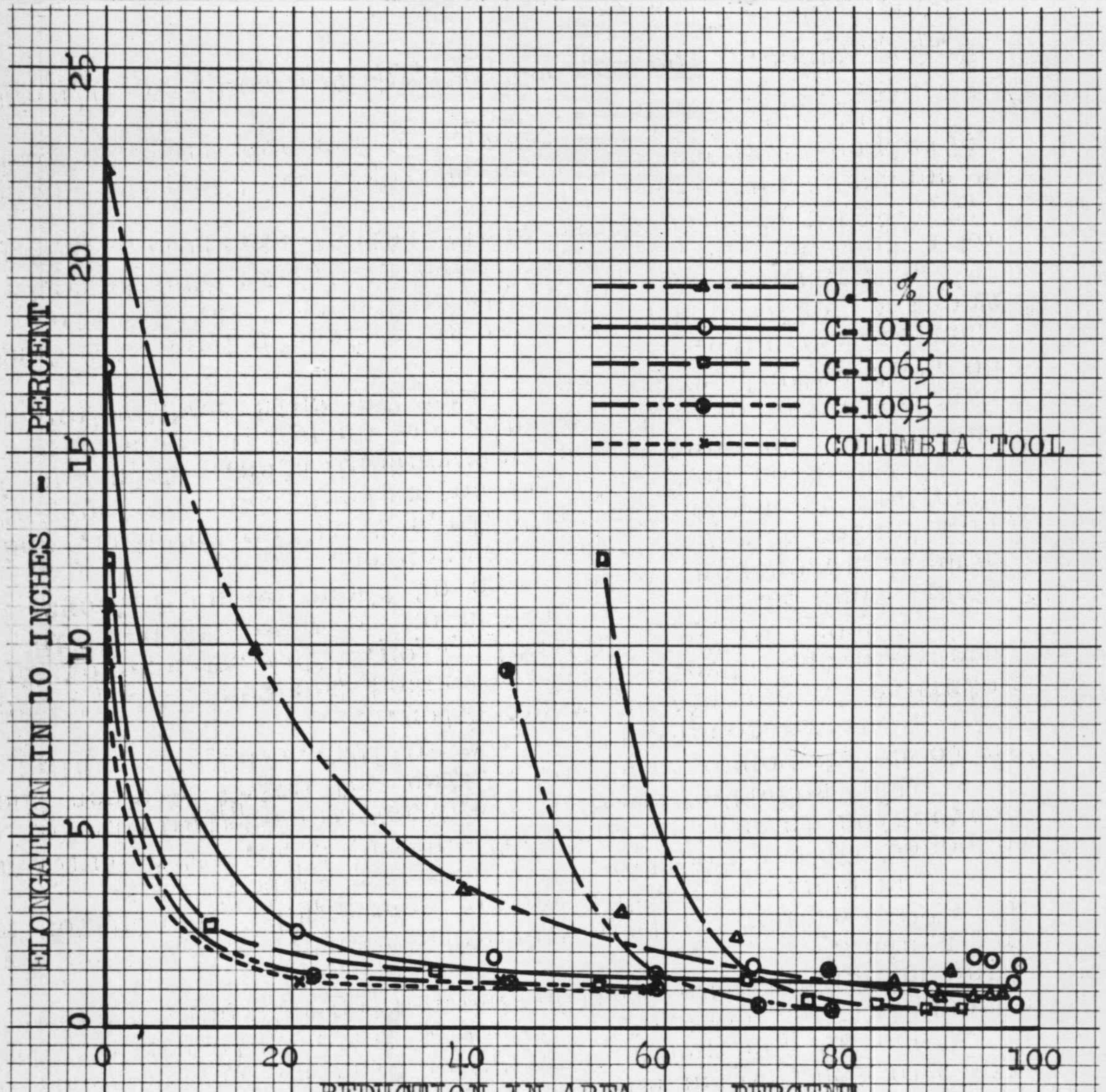


Figure 12. Reduction in Ductility as a Result of Drawing, as Shown by Tensile Elongation, for Five Carbon Steels

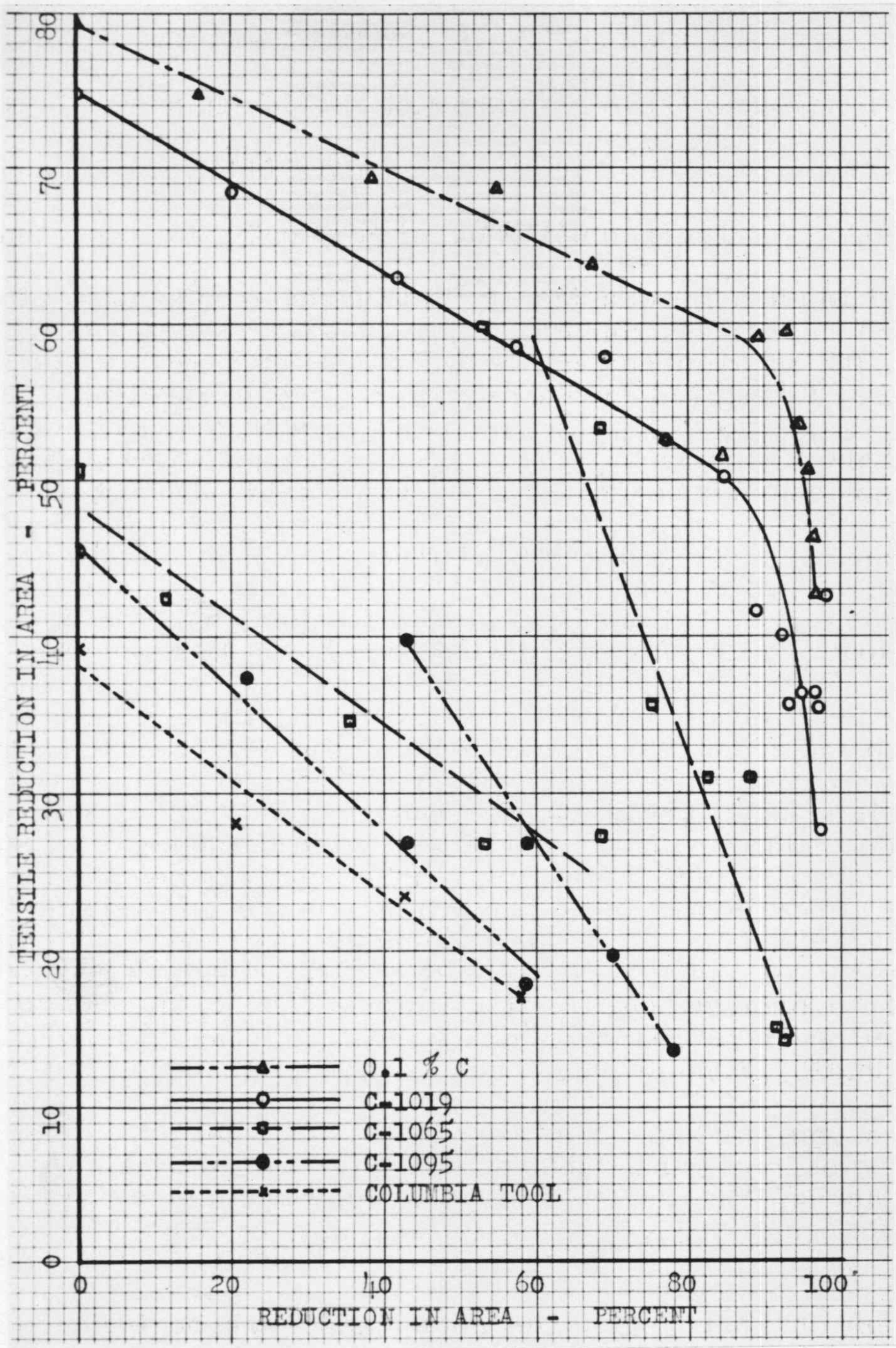


Figure 13. Reduction in Ductility as a Result of Drawing, as Shown by Tensile Reduction in Area, for Five Carbon Steels

result of drawing. The percent elongation appears to decrease very rapidly for small reductions in area, then remains practically the same from twenty percent reduction on, indicating that most of the elongation resulted from the necking down at the fracture point, with much of that measured by the extensometer being elastic, as was also shown by the stress-strain curves.

A nearly linear decrease in ductility for the drawn specimens was shown by the tensile reduction in area, Figure 13. Here again, as for the die pressure, ultimate strength, and hardness, the rate of change with reduction in area was greater after the softening heat treatment than before for the C-1065 and the C-1095 steels. This property also showed a definite change from a linear relation to drawn reduction in area, after the reduction had exceeded about 85 percent, indicating that beyond that point, the wire was definitely over-drawn.

The micrographs of the 0.1 percent carbon steel and the C-1019 steel, Figures 16 and 17 respectively, show similar type grain distortion due to drawing on the longitudinal sections, and an apparent grain refinement on the cross sections of the drawn wires. The higher carbon steels showed a granular structure, Figures 18 and 19, however, magnification of 2000 diameters failed to resolve a lamellar structure within the grains. After the

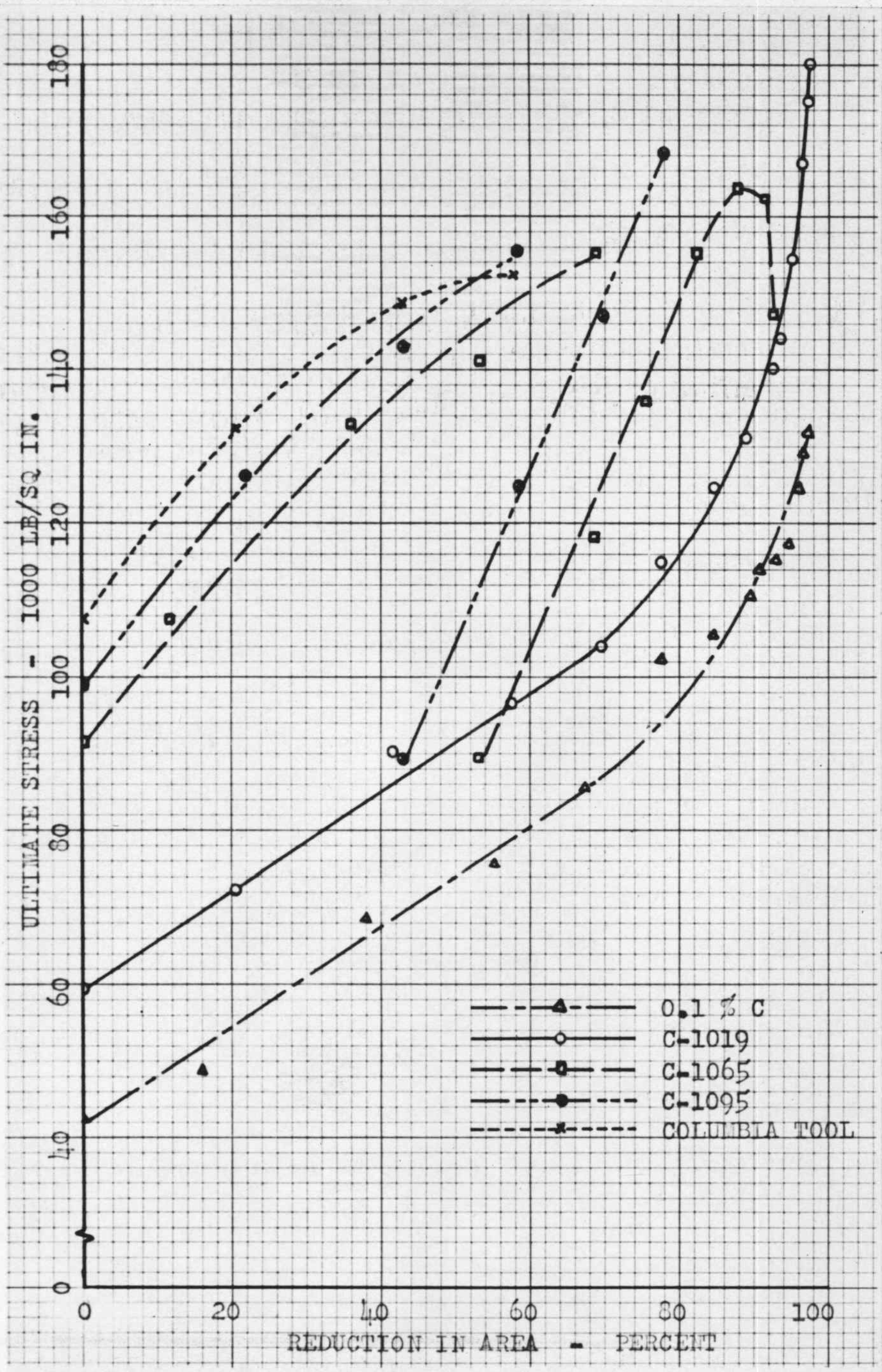


Figure 14. Variation of Ultimate Strength with Drawn Reduction in Area for Five Carbon Steels

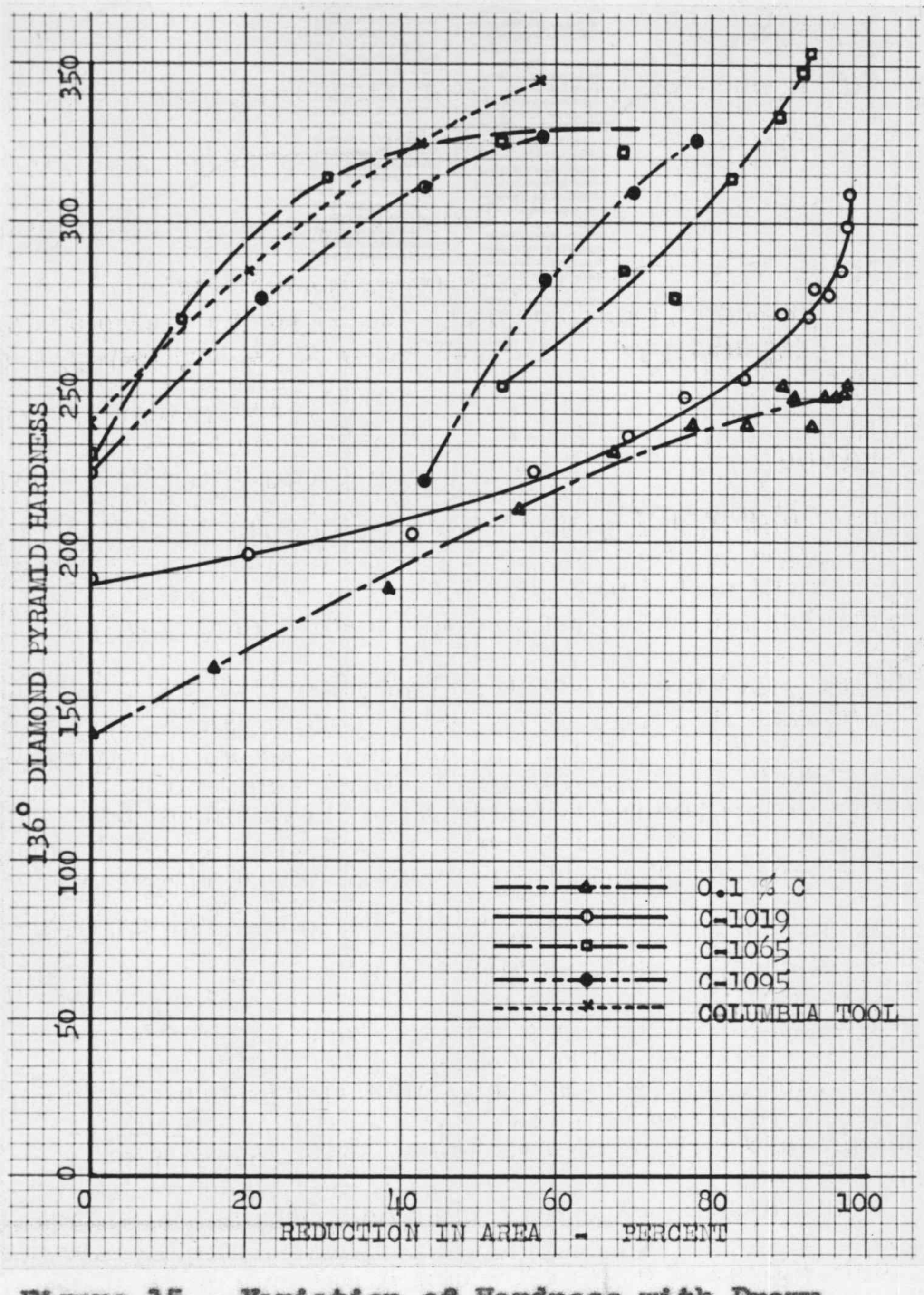


Figure 15. Variation of Hardness with Drawn Reduction in Area for Five Carbon Steels

softening heat treatment on the C-1065 and C-1095 steels, the grains were re-formed, but the structure was very much finer than in the original specimens, indicating that excessive cold work is an aid to grain refinement. Tensile tests showed these finer grained specimens were not as strong as the originals, however, more ductile. The structure of the C-1095 specimen after softening, did not appear exactly granular, but more of the sorbitic type.

As another indication that the cold-worked steels could be readily recrystallized, the ends of some of the specimens which had been sawed off with a hack saw showed complete recrystallization near the cut, gradually giving way to the distorted grains within.

As a summary of the effects attainable by wire drawing, a review of the changes produced in the C-1019 steel will be considered. The specimen was reduced in section by 98 percent in fifteen drafts, the tensile strength was increased from 59,500 to 198,000 pounds per square inch, the 136 degree Diamond Pyramid Hardness from 178 to 309, the tensile reduction in area from 74.8 to 27.8, and one inch of original wire was drawn to 48.7 inches in length.

(1)

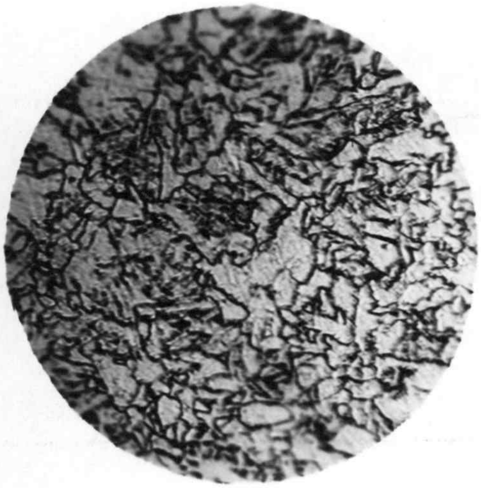
(2)

(3)

(4)

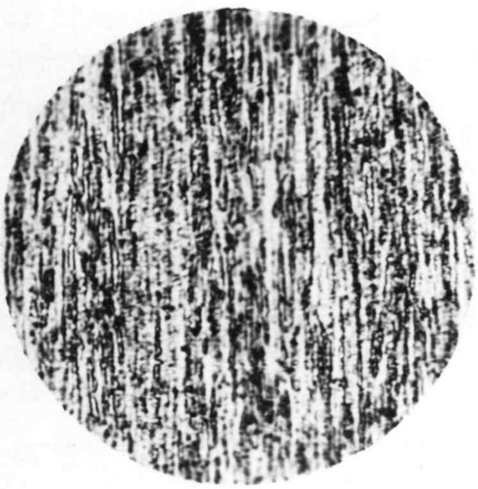
Figure 16. Micrographs of 0.1 percent Carbon Steel, 200X

(1) Original specimen; (2) Longitudinal section after 5 draws; (3) Longitudinal section after 10 draws; (4) Cross section after 10 draws.

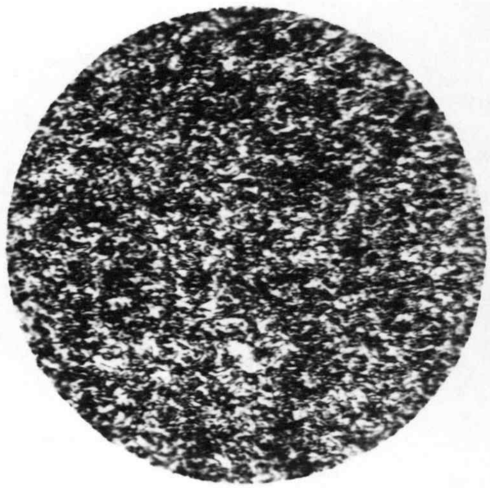


(1)

(2)



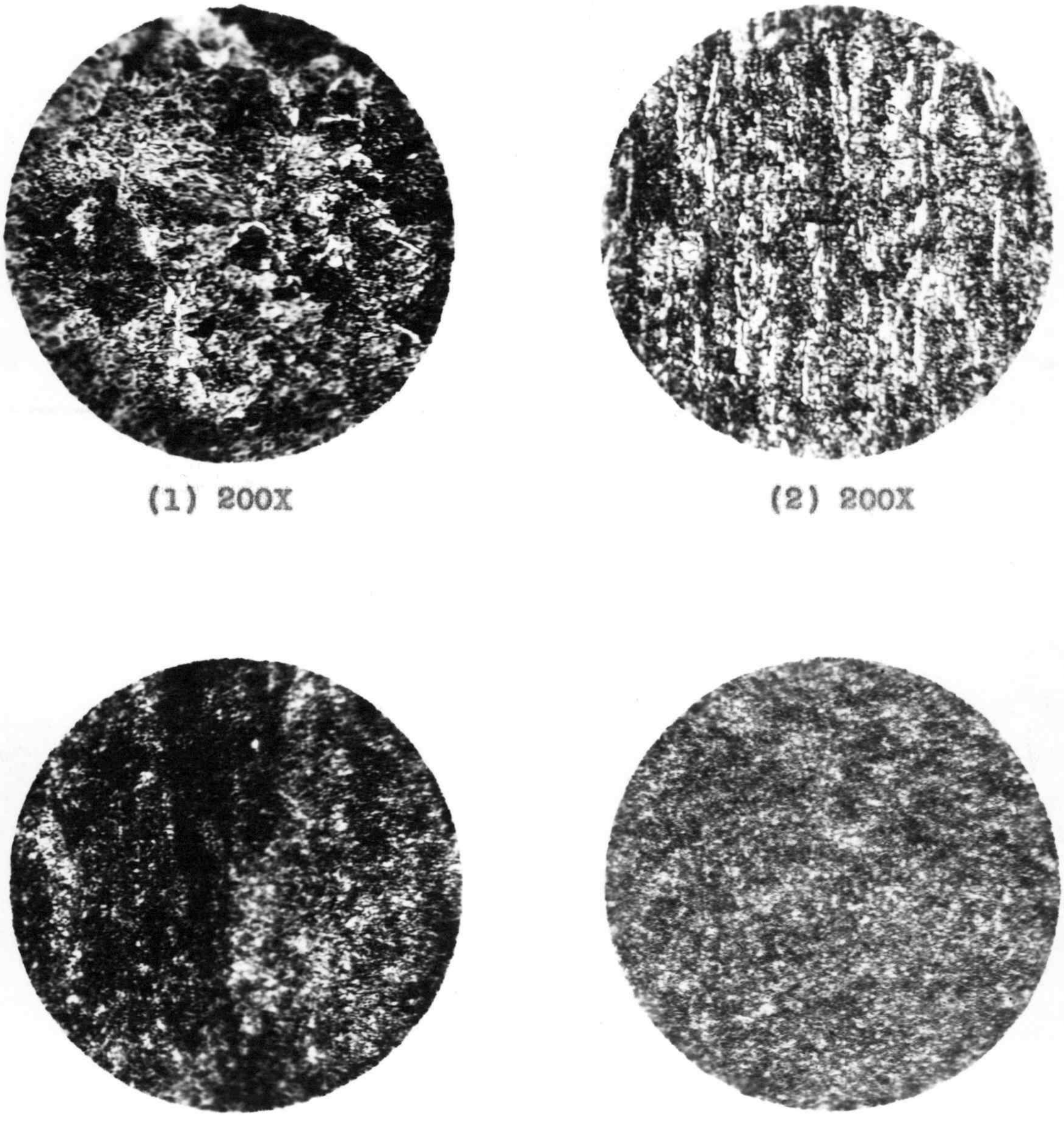
(3)



(4)

Figure 17. Micrographs of C-1019 Steel, 200X

(1) Original specimen; (2) Longitudinal section after 3 draws; (3) Longitudinal section after 8 draws; (4) Cross section after 8 draws.



(1) 200X (2) 200X

(3) 200X (4) 500X

Figure 18. Micrographs of C-1065 Steel

(1) Original specimen; (2) Longitudinal section after 4 draws; (3) Same specimen after heat softening; (4) Cross section after 8 draws.

(1) 200X

(2) 500X

(3) 200X

Figure 19. Micrographs of C-1095 and Columbia Tool Steel

(1) Original specimen of C-1095; (2) C-1095 after softening heat treatment; (3) Original Columbia Tool Steel.

CONCLUSIONS

Wire-drawing has been shown to be capable of producing extremely great changes in the properties of a metal, but if this cold working be carried to a stage where the particles of one grain are moved until they encroach upon and penetrate into adjacent grains, perhaps until the whole grain be actually torn apart, so that the whole structure is made up of fibers more or less torn apart, then the hardness seems to increase, brittleness increases (3, p144), and the wire is of little use except for its high tensile strength.

The following conclusions can be drawn from the tests conducted, and have been shown by others to be typical:

1. The capacity to withstand cold work is largely determined by the microstructure and cannot be indicated entirely by the physical properties of the material.
2. In a properly drawn steel wire, the grains are not destroyed, but are elongated practically into fibers. Cold flow takes place within the grains, and only incidentally by slip at the grain boundaries.
3. When the grain is fully elongated until it appears as a fiber, it cannot be subjected to further cold work in the same direction without rupture, and when

this occurs to any serious extent, the material is over-drawn. This does not appear to apply to very ductile pure metals and alloys, which can be drawn long after all grain identity is lost (1, p 72).

4. When an attempt is made to reduce the material too much in one pass, the grains are broken, as in a tensile test, before the internal structure can adjust itself to the movement.

TABLE I

SPECIMEN NO. 1, COMMON SOFT STEEL WIRE

Die Size in.	Draw Pull lb	Diameter After Draw	Area After Draw	Reduction in Area, % (From Original)	Reduction in Area, % (From Last Heat)
Orig	-	0.1520	0.0181	-	-
0.140	320	0.1393	0.0152	16.0	16.0
0.120	490	0.1194	0.0112	38.2	38.2
0.102	420	0.1017	0.00815	55.1	55.1
0.087	370	0.0863	0.00585	67.7	67.7
0.073	310	0.0727	0.00415	77.2	77.2
0.061	260	0.0606	0.00288	84.2	84.2
0.0508	200	0.0504	0.00199	89.2	89.2
0.0475	68	0.0569	0.00173	90.7	90.7
0.0410	98	0.0408	0.00131	93.0	93.0
0.0345	103	0.0339	0.00090	94.6	94.6
0.0317	36	0.0314	0.00077	96.0	96.0
0.0285	34	0.0288	0.00065	96.4	96.4
0.0260	32	0.0262	0.00054	97.2	97.2

TABLE II

SPECIMEN NO. 2, C-1019 STEEL

Die Size in.	Draw Pull lb	Diameter After Draw	Area After Draw	Reduction in Area, % (From Original)	Reduction in Area, % (From Last Heat)
Orig	-	0.1830	0.0263	-	-
0.164	625	0.1635	0.0210	20.2	20.2
0.140	775	0.1397	0.0153	41.8	41.8
0.120	625	0.1196	0.0112	57.4	57.4
0.102	575	0.1018	0.0081	69.3	69.3
0.087	435	0.0867	0.0059	77.6	77.6
0.073	400	0.0727	0.0042	84.1	84.1
0.061	310	0.0606	0.0029	89.0	89.0
0.0508	235	0.0500	0.0020	92.5	92.5
0.0475	70	0.0472	0.00175	93.4	93.4
0.0410	124	0.0410	0.00132	95.0	95.0
0.0345	124	0.0340	0.00091	96.5	96.5
0.0317	55	0.0317	0.00079	97.2	97.2
0.0285	50	0.0288	0.00065	97.6	97.6
0.0260	40	0.0263	0.00054	98.0	98.0

TABLE III

SPECIMEN NO. 4, C-1065 STEEL

Die Size in.	Draw Pull lb	Diameter After Draw	Area After Draw	Reduction in Area, % (From Original)	Reduction in Area, % (From Last Heat)
Orig	-	0.1740	0.0238	-	-
0.164	590	0.1635	0.0210	11.8	11.8
0.140	1230	0.1397	0.0153	35.7	35.7
0.120	975	0.1196	0.0112	53.0	53.0
0.102	850	0.1018	0.0081	68.5	68.5
0.120	-	0.1196	0.0112	53.0	-
0.102	605	0.1018	0.0081	68.5	27.7
0.087	475	0.0867	0.0059	75.2	47.3
0.073	435	0.0727	0.0042	82.4	62.5
0.061	340	0.0606	0.0029	88.0	74.2
0.0508	255	0.0500	0.0020	91.7	82.2
0.0475	83	0.0572	0.00175	92.4	84.4

TABLE IV

SPECIMEN NO. 5, 0.75/0.90 COLUMBIA TOOL STEEL

Die Size in.	Draw Pull lb	Diameter After Draw	Area After Draw	Reduction in Area, % (From Original)	Reduction in Area, % (From Last Heat)
Orig	-	0.1840	0.0266	-	-
0.164	1300	0.1640	0.0211	20.7	20.7
0.140	1420	0.1397	0.0153	42.6	42.6
0.120	1130	0.1196	0.0112	58.0	58.0
Specimen No. 6, C-1095 Steel					
Orig	-	0.1850	0.0269	-	-
0.164	1050	0.1635	0.0210	22.0	22.0
0.140	1125	0.1397	0.0153	43.2	43.2
0.120	1025	0.1196	0.0112	58.4	58.4
0.140	-	0.1397	0.0153	43.2	-
0.120	720	0.1196	0.0112	58.4	26.8
0.102	665	0.1018	0.0081	70.0	47.2
0.087	560	0.0867	0.0059	78.0	61.5

TABLE V

SPECIMEN NO. 1, COMMON SOFT STEEL WIRE

Die Size in.	Reduction in Area for Draw, Percent	Die Pressure 1000 lb/sq in.	Hardness 136° DPH	Pull/sq in. Red. 1000 lb/sq in.	Drawn Length of 1 Original Inch
Orig	-	-	140	-	1.00
0.140	16.0	61.0	161	110.2	1.19
0.120	26.3	67.8	185	122.4	1.62
0.102	27.2	76.2	210	137.7	2.22
0.087	28.2	88.9	228	160.8	3.10
0.073	29.0	101.0	236	182.2	4.37
0.061	31.0	103.0	236	204.2	6.29
0.0508	31.0	124.2	249	225.0	9.10
0.0475	12.5	144.7	245	262.0	10.47
0.0410	24.6	129.0	236	233.5	13.82
0.0345	31.0	139.0	245	251.0	20.10
0.0317	13.2	153.2	245	277.0	23.55
0.0285	17.7	156.6	247	283.0	27.90
0.0260	16.9	161.0	249	290.0	33.50

TABLE VI

SPECIMEN NO. 2, C-1019 STEEL

Die Size in.	Reduction in Area for Draw, Percent	Die Pressure 1000 lb/sq in.	Hardness 136° DPH	Pull/sq in. Red. 1000 lb/sq in.	Drawn Length of 1 Original Inch
Orig	-	-	178	-	1.00
0.164	20.2	65.3	196	118.0	1.25
0.140	27.1	75.2	201	136.0	1.71
0.120	26.8	84.3	222	152.0	2.35
0.102	27.7	102.6	233	185.0	3.25
0.087	27.2	109.3	245	198.0	4.46
0.073	28.8	130.1	251	235.0	6.27
0.061	31.0	131.7	272	238.0	9.07
0.0508	31.0	144.5	270	261.0	13.15
0.0475	12.5	154.8	279	280.0	15.03
0.0410	24.6	159.5	276	288.5	19.94
0.0345	31.0	168.5	285	305.0	28.90
0.0317	13.2	253.0	299		33.30
0.0285	17.7	197.5	309	357.5	40.50
0.0260	16.9	210.0	309	363.5	48.70

TABLE VII

SPECIMEN NO. 4, C-1065 STEEL

Die Size in.	Reduction in Area for Draw, Percent	Die Pressure 1000 lb/sq in.	Hardness 136° DPH	Pull/sq in. Red. 1000 lb/sq in.	Drawn Length of 1 Original Inch
Orig	-	-	227	-	1.00
0.164	11.8	116.5	268	210.5	1.13
0.140	27.1	129.0	314	216.0	1.55
0.120	26.8	131.5	325	238.0	1.95
0.102	27.7	151.5	322	274.0	2.94
0.120	-	-	249	-	1.95
0.102	27.7	108.0	285	195.3	2.94
0.087	27.2	119.3	276	216.0	4.03
0.073	28.8	141.5	314	256.0	5.67
0.061	30.9	144.6	333	262.0	8.21
0.0508	31.0	156.8	348	284.0	11.90
0.0475	12.5	183.6	354	332.0	13.62

TABLE VIII

SPECIMEN NO. 5, 0.75/0.90 COLUMBIA TOOL STEEL

Die Size in.	Reduction in Area for Draw, Percent	Die Pressure 1000 lb/sq in.	Hardness 136° DPH	Pull/sq in. Red. 1000 lb/sq in.	Drawn Length of 1 Original Inch
Orig	-	-	236	-	1.00
0.164	20.7	130.8	285	236.5	1.26
0.140	27.5	135.3	325	245.0	1.74
0.120	26.8	153.5	245	275.5	2.38

Specimen No. 6, C-1095 Steel

Die Size in.	Reduction in Area for Draw, Percent	Die Pressure 1000 lb/sq in.	Hardness 136° DPH	Pull/sq in. Red. 1000 lb/sq in.	Drawn Length of 1 Original Inch
Orig	-	-	222	-	1.00
0.164	21.9	98.5	276	178.0	1.28
0.140	27.1	109.2	312	197.5	1.76
0.120	26.8	138.4	327	250.0	2.40
0.140	-	-	218	-	1.76
0.120	26.8	97.2	281	175.5	2.40
0.102	27.7	118.7	309	214.5	3.32
0.087	27.2	141.0	325	254.4	4.57

TABLE IX

SPECIMEN NO. 1, COMMON SOFT STEEL WIRE

Die Size in.	Fracture Load lb	Ultimate 1000 lb/sq in.	Test Elongation in. in 10 in.	Test Elongation Percent	Fracture Diameter in.	Reduction in Area, % (Tensile Test)
Orig	770	42.4	2.24	22.4	0.068	79.5
0.140	745	48.8	0.99	9.9	0.070	74.7
0.120	730	65.2	0.36	3.6	0.066	69.4
0.102	615	75.8	0.30	3.0	0.057	68.7
0.087	500	85.5	0.24	2.4	0.052	63.8
0.073	425	102.3	0.15	1.5	0.050	52.8
0.061	305	105.8	0.12	1.2	0.042	51.7
0.0508	220	110.5	0.09	0.9	0.035	51.8
0.0475	196	114.0	0.15	1.5	0.030	59.0
0.410	151	115.2	0.07	0.7	0.026	59.5
0.0345	106	117.8	0.09	0.9	0.024	53.3
0.0317	96	124.7	0.10	1.0	0.022	50.6
0.0285	84	129.2	0.08	0.8	0.021	46.2
0.0260	71	131.5	0.07	0.7	0.020	42.6

TABLE X

SPECIMEN NO. 2, C-1019 STEEL

Die Size in.	Fracture Load lb	Ultimate 1000 lb/sq in.	Test Elongation in. in 10 in.	Test Elongation Percent	Fracture Diameter in.	Reduction in Area, % (Tensile Test)
Orig	1566	59.5	1.17	17.1	0.092	74.8
0.164	1665	72.2	0.25	2.5	0.092	68.3
0.140	1382	90.4	0.18	1.8	0.085	63.0
0.120	1080	96.4	0.16	1.6	0.077	58.4
0.102	842	104.0	0.16	1.6	0.066	57.8
0.087	679	115.0	0.15	1.5	0.060	52.6
0.073	522	124.5	0.09	0.9	0.052	50.1
0.061	375	131.0	0.10	1.0	0.047	41.4
0.0508	280	140.0	0.05	0.5	0.039	40.0
0.0475	252	144.0	0.18	1.8	0.038	35.5
0.0410	204	154.5	0.18	1.8	0.030	46.2
0.0345	152	167.0	0.10	1.0	0.025	46.2
0.0317	137	175.0	0.12	1.2	0.027	27.8
0.0285	117	180.0	0.06	0.6	0.023	35.4
0.0260	105	198.0	0.16	1.6	0.020	42.7

TABLE XI

SPECIMEN NO. 4, C-1065 STEEL

Die Size in.	Fracture Load lb	Ultimate 1000 lb/sq in.	Test Elongation in. in 10 in.	Test Elongation Percent	Fracture Diameter in.	Reduction in Area, % (Tensile Test)
Orig	2174	91.4	1.22	12.2	0.123	50.5
0.164	2248	107.5	0.26	2.6	0.124	42.4
0.140	2036	133.0	0.15	1.5	0.113	34.6
0.120	1578	141.0	0.11	1.1	0.102	26.8
0.102	1258	155.4	0.13	1.3	0.087	27.2
0.120	903	89.3	1.23	12.3	0.076	59.8
0.102	955	118.0	0.13	1.3	0.070	53.1
0.087	804	136.0	0.07	0.7	0.070	35.6
0.073	620	155.0	0.06	0.6	0.061	31.0
0.061	474	163.5	0.05	0.5	0.051	31.0
0.0508	325	162.5	0.03	0.3	0.046	15.0
0.0475	257	147.0	0.02	0.2	0.043	14.3

TABLE XII

SPECIMEN NO. 5, 0.75/0.90 COLUMBIA TOOL STEEL

Die Size in.	Fracture Load lb	Ultimate 1000 lb/sq in.	Test Elongation in. in 10 in.	Test Elongation Percent	Fracture Diameter in.	Reduction in Area, % (Tensile Test)
Orig	2865	107.8	0.96	9.6	0.144	39.1
0.164	2798	132.5	0.12	1.2	0.139	28.0
0.140	2269	148.3	0.14	1.4	0.122	23.5
0.120	1708	152.4	0.10	1.0	0.109	17.0
Specimen No. 6, C-1095 Steel						
Orig	2659	99.0	1.11	11.1	0.137	45.4
0.164	2646	126.0	0.13	1.3	0.130	37.2
0.140	2188	143.0	0.12	1.2	0.120	26.8
0.120	1740	155.4	0.11	1.1	0.108	17.9
0.140	1375	89.8	0.93	9.3	0.108	39.9
0.120	1400	125.0	0.14	1.4	0.102	26.8
0.102	1188	147.0	0.06	0.6	0.091	19.8
0.087	982	168.2	0.05	0.5	0.081	13.5

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