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OF THE

MICHIGAN COLLEGE

OF

MINING AND TECHNOLOGY

COPPER WIRE

A Correlation of the Tensile Strength and Electrical Conductivity of Hard-Drawn Copper Wire With Preferred Orientation

by

ROY WARD DRIER

NEW SERIES JANUARY, 1936 VOL. 9, No. 2

HOUGHTON, MICHIGAN

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A Correlation of the Tensile Strength and Electrical Conductivity of Hard-Drawn Copper Wire with Preferred Orientation

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Abstract

Wire drawing is reviewed from antiquity to the present, with particular emphasis on present day drawing of copper wire. Unit cell orientation is deduced from micrographs and various types of X-ray spectra. These orientations are correlated with electrical conductivity and tensile strength, and explanations for the variations due to cold drawing are formulated. Similar correlation is done for copper wire, cold-drawn in various manners. Tensile strength does not vary appreciably but the electrical conductivity seems to be higher for wire drawn continuously than for wire whose direction of drawing is reversed. ✦ ✦ ✦ ✦

Introduction

TUBAL CAIN, the first "cunning artificer in metals," was in all probability the first producer of wire. Records of early Egypt mention metallic filaments or threads[1], some of which have been found to date back to 1700 B. C. The second book of Moses states that the sacerdotal robes of Aaron were decorated with "gold beaten into thin plates and cut into wires." Wire made in Nineveh in the ninth century B. C. is exhibited in the Kensington Museum. Wire is mentioned in the works of Homer and Pliny. In the Portici Museum are exhibited metal heads with metallic hair which were found in the excavations at Herculaneum.

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IN antiquity wire was produced by hammering out strips of metal. It was not until the fourteenth century A. D. that it was formed from rods drawn through metal dies. The histories of Augsberg and Nuremburg, Germany, mention the "drahtzieher," or wire drawer. Conrad Celtes, writing in the fourteenth century, mentions the hand-drawing of wire in a Nuremburg wire mill owned by a man called Rudolph. The first wire-drawing in France was done by Richard Archal in 1500, and some classes of wire are still known as "fil d' Archal".

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IN Great Britain the first machine-drawn wire was made in the middle of the sixteenth century, water power being used as the source of energy. It is interesting to note that two Saxons had to obtain permission from Queen Elizabeth to establish this mill and that for this privilege she was sup-

The work presented constitutes a part of the author's thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy in Metallurgical Engineering at the Michigan College of Mining and Technology.

plied with toilette pins from the mill.

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WIRE-DRAWING was introduced into the United States about 1830. Roebling and Sons established their business in 1849.

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Copper Wire Drawing

COPPER which is to be drawn into wire is first cast into bars about 4 by 4 in. in cross-section, about 5 ft. in length, and weighing between 200 and 250 lb. The molds are made of copper, and the ratio of mold weight to casting is usually about 5 to 1. Much of the copper drawn into wire is cast by hand. A good casting temperature for hand-cast wire bars is 1125° C. (2060° F.) The molds are set in 4 or 5 in. of water to expedite the cooling and thus keep the mold temperature from rising to a point where the casting and the mold fuse. In fact, practice has shown that it is advisable to keep the mold as near a temperature of 125° C. as possible all through the casting operation. Before each pour the interior of the mold is sprayed with a wash to keep the copper from adhering to the mold; this coating causes the splashings which strike the sides to drop back into the molten copper. It is good practice to remove the bar as soon as the copper has set.

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MOST wire bars are cast from primary copper, though the Western Electric Company reports satisfactory bars cast from remelted and refined clean secondary copper. [2] Dewald[3] reported improved wire and better drawing to sizes smaller than 24 B. & S. from a wire bar composed of small crystals rather than of medium or coarsely crystalline material. Discussions of this by Crampton[3] and by Schneider[3] seemed to indicate that grain-size in the wire bar has no effect on the final wire. It is difficult to see how the original grain size would have much final effect, for recrystallization occurring at some time during the hot-rolling completely destroys the original structure. It is conceivable that the power requirements for the rolling of finely crystalline and of coarsely crystalline materials might differ, and it might be deduced from general considerations that the more coarsely crystalline material would require less power; but it is the consensus of opinion that equally good wire can be drawn from wire bars differing only in grain-size—that is from either coarsely or finely crystalline stock.

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Comparison of Bars Cast Vertically and Horizontally

SCOTT and Dewald[4] compared copper wire bars vertically cast with those horizontally cast. They found that if the set face of a horizontally-cast bar were machined off, the bar responded to mill treatment more satisfactorily than the unmachined bars. They concluded that improved wire and wire drawing would result from the elimination of as much of the wrinkled surface as possible and from an increase of density, both of which would be accomplished by the use of a vertical mold. Their results showed that, in general, copper wire bars cast vertically were superior to those cast horizontally. They concluded that inasmuch as electrical conductivity varies directly with the density, the increase in density would result in an increase in conductivity, a conclusion which agreed with the findings of Masing and Hasse.[5] Since the density after cold-drawing was the same, 8.91, regardless of the initial density or of method of casting, it does not necessarily follow that a method of casting denser copper would result in higher electrical conductivity. Scott and Dewald[4] showed an average increase in conductivity of 0.20 per cent, a lower tensile strength, and a higher elongation for the vertically cast copper as compared with the horizontally cast. Skowronski, in his discussion of this work, suggested that the difference in the conductivity might well have been due to a variation in the oxygen content.

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ALL of the foregoing efforts toward improving wire bars were in the right direction, but did not result in any marked improvement. In 1930 a round-table discussion of wire bars and their processing led to the consideration of a possible method for eliminating the steps between the casting of the wire bar and its subsequent rolling to ½-in. rod.

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Experiments in New Methods of Producing Copper Rod and Wire

VARIOUS schemes were conceived, such as extruding a ½-in. section from the molten bath at a rate which would permit cooling so that a solid rod would result. Another scheme was the tapping of the copper from near the bottom of the bath, through a water-cooled orifice. It was planned to exert a slight pull on the rod, by entering it in rolls placed close to the orifice. The procedure which seemed the most practical was that suggested by F. J. Kohlhaas. In accordance with his plan, which is now in the experimental stage, the copper is tapped from the molten bath into ⅝-in. grooves on a horizontal, revolving plate. The rate and temperature of pouring, the rate of travel of the plate, and the temperature of the plate are so adjusted that the rod is solid and can be shunted off the plate after it has completed approximately two-thirds of a revolution. Samples of this section were rolled to a 5/16-in. rod and then cold-drawn to No. 12 B. & S. wire, according to standard commercial practice.

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THE resulting wire fulfills all A. S. T. M. specifications. Of course many difficulties will be encountered and will have to be straightened out before such an

innovation will be put in the regular flow-sheet; but when one considers the possibility of multiple-grooved plates, of controlled atmosphere in the pouring chamber, of placing the rolls and wire-drawing machines immediately adjacent to the grooved plate, and of the savings due to elimination of the pre-rolling heating and the rolling itself, this procedure promises to be the most outstanding improvement in wire-drawing practice in the last few decades.

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Present Commercial Practice

COMMERCIAL practice at present takes the wire bar, heats it to approximately 870° C. (1600° F.), and then reduces it by a series of rolls to a rod of the desired size for drawing, usually 5/16-in. in diameter. The bars are advanced through the furnace through three distinct zones, are discharged at approximately 870°C. (1600° F.), and are then conveyed to the first set of rolls. A bar is reduced through a series of alternate squares and ovals to the desired size. A ¾-in. rod will have undergone 10 passes; a 5/16-in. rod 16. The reductions vary from 40 per cent in the bar section to 10 per cent in the finishing pass. Modern furnaces with single-line finishing will average from 12 to 14 tons of 5/16-in. rod per hour. The efficiency of modern plants is high. An installation such as that described will have a scrap loss of but 0.5 per cent.

Some Causes of Defects in Copper Wire

SOME final defects in the wire can be traced to the rolling of the wire bar, but the practice is now so standardized that few defects are due to this operation.

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THE rod as it comes from the final roll is found to be coated with a black oxide which is removed by immersing for a half hour in a dilute sulphuric acid pickling solution. A concentration of 3 to 5 per cent acid and a temperature of 54° C. are optimum. Higher temperatures require higher acid concentrations. Adhering acid and scale are then removed by hosing with pressure water, and the rod is then dipped in a neutralizing solution which, besides the neutralizing ingredient, contains some agent designed to give the rod a coating that will prevent further oxidation.

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THE above operations are all preliminary to the actual wire-drawing. The rod is now in a softened condition ready for drawing. It can be reduced to the desired size by either of two processes: by continuous drawing through a series of dies of decreasing diameter, or by passing through the same dies, singly, the direction of drawing being reversed after each pass. This single-block method necessitates coiling the wire after each pass. The final section of this thesis discusses the effects of alternating the direction of drawing.

Rate of Reduction, Rod to Wire

THOUGH reductions of 50 per cent in cross-section are possible, the accepted reduction in commercial wire-drawing is slightly more than 20 per cent per die. Coarse and medium-fine wire are drawn through dies of chilled cast iron, hard steel, tungsten carbide, or tantalum carbide. The finer sizes of wires are drawn through diamond dies. A detailed treatment of dies, lubrication, power, and other phases of wire-drawing technique is deferred for the present.

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*Ultimate Structure, Electrical Conductivity, and Tensile Strength

THE conductivity of copper wire is of prime importance to the electrical industry and, consequently, to the copper refiner and the wire manufacturer; tensile strength, though of lesser, is still of great importance. Annealed copper wire has a higher electrical conductivity than hard-drawn—often over 100 as compared with 96 or 97. Hard-drawn wire, conversely, has a tensile strength of 70,000 lb. per sq. in. as compared with 30,000 for annealed wire. The following experiments were carried on in an attempt to explain some of the reasons for these changes in properties, or at least to correlate the different structural conditions with the physical properties.

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Samples

THE samples selected for use in the diffraction work and resistivity measurements were taken from Nos. 6, 8, 10, and 12 gauge (B. & S.) commercial wire, both hard-drawn and annealed. The wire was produced from standard 220-lb. wire bars, hot-rolled to 5/16-in. and cold-drawn in one direction to size. In addition, observations were made on 10-gauge wire, which was drawn from a piece of native copper without melting. For annealing, the wires were kept at a temperature of 820° C for one hour and fifteen minutes. Table I gives the composition and conductivity of the wires in this first set of experiments.

*R. W. Drier and C. T. Eddy: Correlation of the Ultimate Structure of Hard-drawn Copper Wire with the Electrical Conductivity. Trans. A. I. M. E. (1930), 89, Institute of Metals Division.

TABLE I
Composition and Conductivities of Wires Discussed

Wire	Metal Content (Cu Ag.)	As	Conductivity (per cent)
No. 12 Hard drawn	99.94	.000378	97.7
No. 6 Hard drawn	99.94	.000378	97.8
No. 6 Annealed	99.93	.000370	99.8
No. 10 Hard drawn from Native Cu.	99.96	.000310	99.8
No. 10 Same as No. 10 above but annealed	99.96	.000310	102.5

IN order to study the changes in ultimate structure from the surface to the core of the wire and to observe any variations in conductivity which may accompany these structural changes, observations were made on wires whose outer layers were removed in successive stages by dissolution in 25 per cent nitric acid. The etching was carried on in such a manner that the diameters of the wires were reduced in stages of approximately 0.5 mm. Various methods of etching were tried, all of which yielded identical results. The method which was finally adopted consisted of placing the wires in a nearly vertical position in a cylinder and causing them to rotate by mechanically circulating the solution. For each stage, after one-half of the etching was accomplished, the wire was turned end for end in the solution and the etching completed. It was generally observed that as the hard-drawn wires etched, the cross-section gradually became elliptical. The difference between the lengths of the major and the minor axes of the cross-section at the core was found to be as great as 50 per cent. It seems quite probable that this was residual from the last oval pass in the rolls. Some wires etched with annular rings. A microscopical examination of these rings at 1600 diameters failed to show any peculiar structures not noticeable in the rest of the wire, and it was thought that possibly the rings were a result of chattering. (Fig. 1.)

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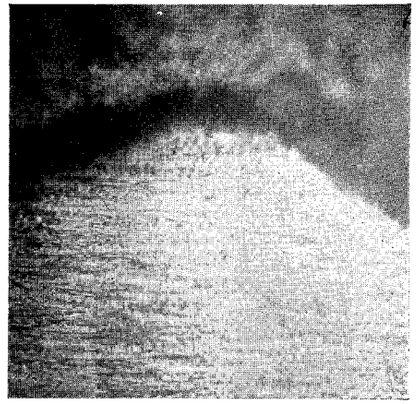

Fig. 1, 1600X—Micrograph of Ringed Portion of Cross-Section of Wire Which Showed Annular Rings upon Etching. ✦ ✦ ✦

HULL diffraction patterns were obtained from samples immediately adjacent to those used for resistivity measurements. In addition, diffraction patterns were taken of the original wires (those used for the resistivity measurements) before etching and also after the last etching had been made and the resistivity determined. These latter patterns agreed precisely with the first and last patterns of the series made from a single wire. (Fig. 2.)

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A NUMBER of wires were ground off until a longitudinal section was exposed through the core. They were polished, etched, and examined microscopically at 1660 diameters. Micrographs of a section from the surface through the core to the opposite surface are given in Fig. 3. Elongated grains showing slip structure exist throughout the whole section, the grains being elongated in the direction of drawing. It will be seen that the slip lines make various angles with the drawing direction. Near the surfaces of the wire there prevails a 45° slip angle, with a few slip-lines at right angles to the wire axis. As the core is approached, the 45° angle disappears almost entirely, and the lines at 90° almost hold their own. Evidently the drawing deformation has effected at the core some type of orientation in which the planes of easiest slip do not make 45° with the drawing force. In fact, as the core is approached, slip-lines increasingly lack definition until they are not in evidence at all. This phenomenon will be considered later in the light of the orientations deduced from X-ray diffraction examination.

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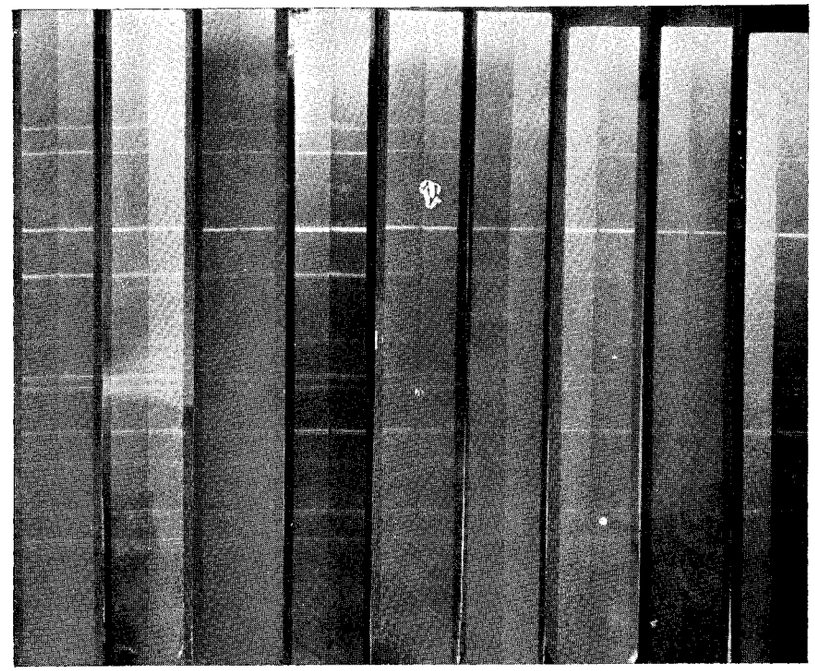
AN end cross-section of the wire was also polished and examined. No difference was notice-



1 2 3 4 5 6 7 8 9

Fig. 2—Hull Spectra of No. 6 B. and S. Cold-Drawn Copper Wire in the Successive Stages of Etching. Diameter of Wire After Etching and Before Raying

1. 4.115 mm.
2. 3.5 mm.
3. 2.96 mm.
4. 2.35 mm.
5. 1.95 mm.
6. 1.15 mm.
7. 0.45 mm.
8. 0.25 mm.
9. 0.13 mm.

1.

2.

Fig. 3. 1600-X—First Two of a Series of Nine Micrographs Which Includes the Entire Cross-Section of a Wire.

3.

4.

Fig. 3. Cont.—Second Two of a Series of Nine Micrographs Which Includes the Entire Cross-Section of a Wire.

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Fig. 3. Cont. 1600-X—Fifth of a Series of Nine Micrographs Which Includes the Entire Cross-Section of a Wire. This is a Micrograph of the Core.

able across the wire, though the Rockwell hardness of the core was greater than that near the surface.

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Diffraction

THE diffraction work was done on a General Electric unit, using a molybdenum, water-cooled target Coolidge tube which operated at 20 ma. and 30,000 volts. The familiar Hull cassette with Zirconium dioxide filters as an integral part of the cassette was used. The filters permit transmittance of radiation which approximates the monochromatic.

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POLYCHROMATIC pinhole spectra were also obtained of all samples (Fig. 4.), and several spectra were made of some of the cores, rotating crystal and oscillating crystal methods being used. (Fig. 5.)

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IN obtaining the Hull spectra, of the larger wires at least, the sample was so placed that the X-rays just grazed the surface of the wire. As the wires were reduced by etching, they finally arrived at the size at which the X-ray beam was wider than the sample and so bathed both sides. Both Hull and pinhole spectra were obtained of the surface of all wires after each etching. The patterns were so similar that a single series can be used as representative of them all. Fig. 2 shows such a representative series of Hull spectra. It includes the diffraction spectra of the No. 6 B. & S. hard-drawn

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Fig. 3. Cont. 1600-X—Sixth and Seventh of a Series of Nine Micrographs Which Includes the Entire Cross-Section of a Wire.

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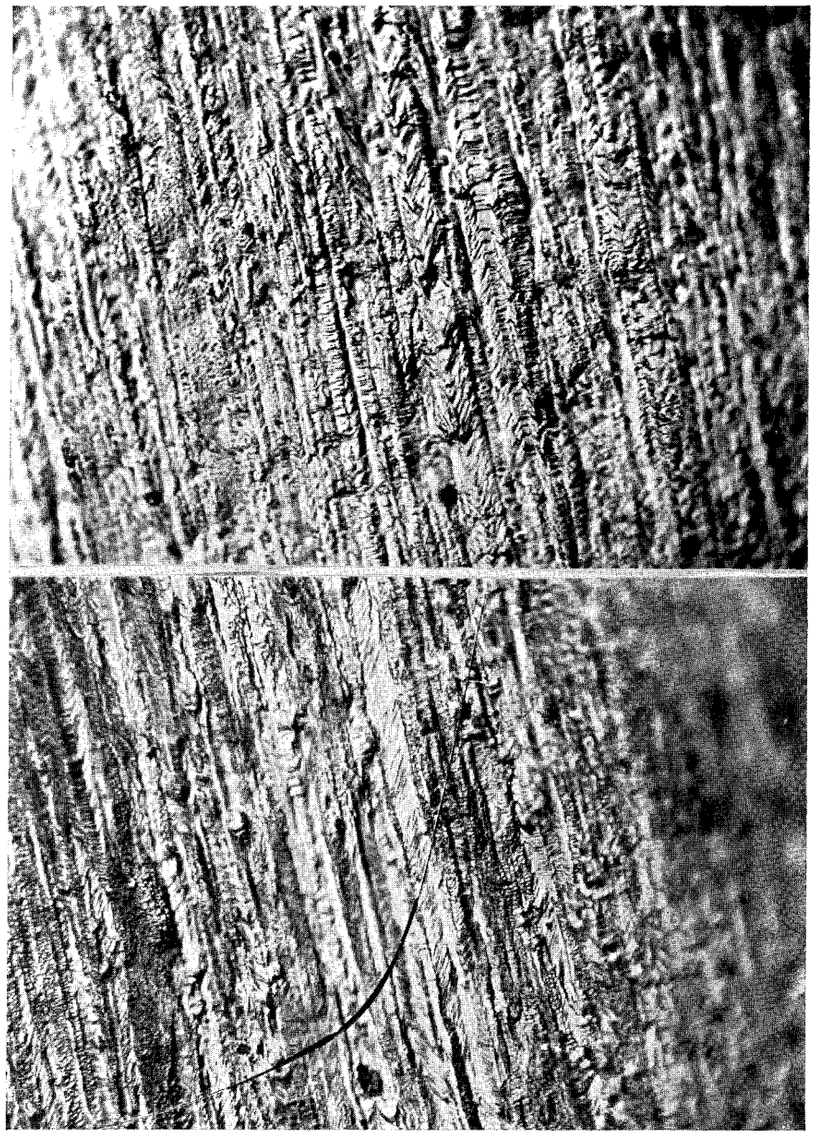

Fig. 3. Cont. 1600-X—Eighth and Ninth of a Series of Nine Micrographs Which Includes the Entire Cross-Section of a Wire. ✦ ✦ ✦ ✦ ✦ ✦ ✦ ✦ ✦

wire after each separate etching, from the original diameter of 4.12 mm. to its final stage of 0.09 mm. Figs. 6-10, 6-11, and 6-12 show the Hull spectra of No. 6 B. & S. commercially annealed copper wire at the surface and at the core. The similarity among these last three agrees with accepted theories concerning annealed wires.

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FIG. 7 shows two spectra and one micrograph of wire annealed at from 1060° to 1080°C. These spectra indicate not only recrystallization but also a preferred orientation. This is in accord with the theory that hard-drawn copper wire assumes a fiber type of orientation if annealed above 1000°C. Twinning is most prevalent at 90° to the wire axis.

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IN the Hull spectrum series of each of the hard-drawn wires, a certain variation in the relative intensities of the spectral lines was noticed. The reflections from

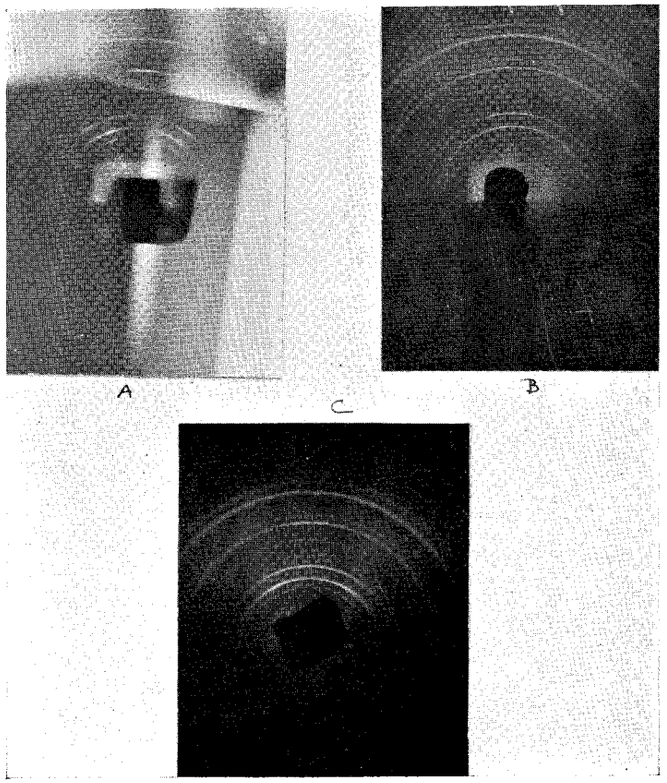

Fig. 4—First Three of a Series of Nine Polychromatic Pinhole Spectra Representing the Structure of Hard-Drawn Copper Wire as One Penetrates from Sur ace to Core. Note that "a" shows a Preferred Orientation at the Surface.

the 200 planes do not vary appreciably in their relative intensities. The reflections from the 111 planes decrease from an intensity practically equal to that of the 110 reflection to an absolute absence. As would be expected, the variations in the intensities of the reflections from the fictitious planes 222 and 333 correspond to the variations in the intensities from the 111 planes. This is not quite true of the line which seemingly comes from the 333 planes. Inasmuch as the d_{333} and the d_{511} are the same, the reflections from both fall on the same place on the film, and because of the 511 planes a small intensity will be expected for this line. By the time the last etching reduction is finished the reflections from the 220 planes practically double their intensity and those from the 311 planes are reduced to approximately half-intensity.

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THE reason for these variations is readily seen by an inspection of the pinhole spectra in Fig. 4. From them one notes that at the surface is a very thin layer of preferredly oriented material, below which is randomly oriented material. As the core is approached the unit cells in the wire are again becoming preferentially oriented. The spectra of the copper just below the surface are composed of complete circles, indicating random orientation, and those from nearer the core seem to have the total intensity of each circle concentrated at certain spots in the circle. The pinhole spectra and also the Hull spectra, which are merely radial sections of pinhole spectra, closely resemble in nature the spectra of fibrous materials, such as asbestos.

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THE preferential orientation first appeared when a diameter of 2.35 mm was reached; this is in fair agreement with Wood's [6] conclusions that the core of a hard-drawn copper wire has a diameter of from 60 to 40 per cent of the

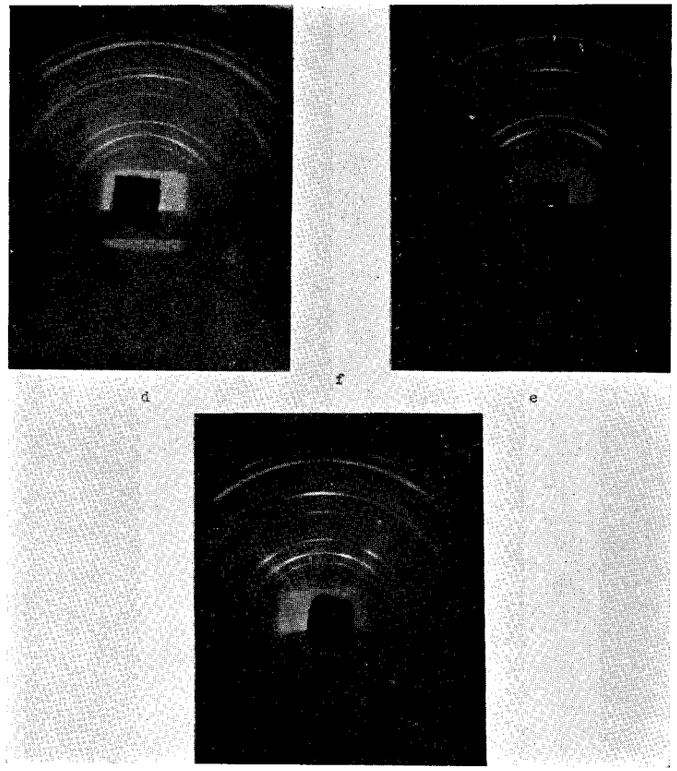

Fig. 4. Cont.—Fourth, Fifth and Sixth of a Series of Nine Polychromatic Pinhole Spectra Representing the Structure of Hard-Drawn Copper Wire as One Penetrates from Surface to Core. Preferred Orientation is very apparent in "f", which is a Spectrum of the Outer Part of the Area. ✦ ✦

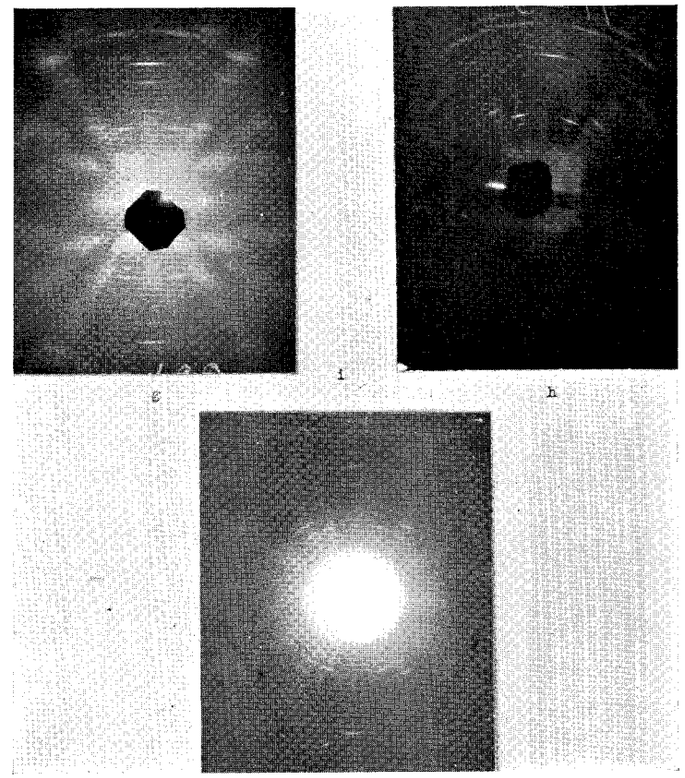

Fig. 4. Cont.—Seventh, Eighth and Ninth of a Series of Nine Polychromatic Pinhole Spectra Representing the Structure of Hard-Drawn Copper Wire as One Penetrates from Surface to Core. The Shortening of the Intensity Maxima Indicates that the Orientation is More Preferred as the Center of the Core is Approached. These Three Show Asymmetry Due to the Conical Orientation. ✦ ✦ ✦

total diameter, varying inversely with the degree of cold reduction to which the wire has been subjected. A Bernal [23] analysis of the pinhole spectra showed that the spectral spots which are present are from planes which would reflect if the unit cells were so oriented that either the 100 direction or the 111 direction would be parallel to the direction of drawing, or in other words to the longitudinal axis of the wire. There is a slight asymmetry of the spots which indicates that the arrangement is not one of exact parallelism but rather one of a conical nature (Fig. 4-g, h, and i).

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A COMPARISON of the spots which are representative of 111 orientation with those of the 100 indicates that the 111 orientations seem to be twice as prevalent. This compares favorably with Schmidt and Wasserman's [7] 60-40 and with Glocker's [8] 50-50 relative importance of the two. The extreme outer surface of the hard-drawn wire has a thin layer of material with a preferential orientation similar to the orientation of the core (Fig. 4a). This is in accord with the conductivities determined and with the results obtained by Harris [9] in his work on the distribution of tensile strength in hard-drawn copper wire. He found that a thin surface layer has a high tensile strength, which decreases as much as 50 per cent for the material between the surface and the core (core diameter being approximately one-half the total wire diameter) and then rises abruptly and remains fairly constant for the core.

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Resistivity Measurements

FOR the determination of the changes in specific resistivity throughout the sections of the wires, measurements were made on the original wires before etching and on the wires after each successive etching.

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THE potentiometric method was used and direct e. m. f. readings were made to 10^{-6} volts. The wires were placed in a special bridge, and mercury end contacts were used to insure parallel lines of flow (especially for the heavier wires). A definite current, accurately measured, was passed through the wires, and the drop in potential between two intermediate knife-edge contacts was measured on a Leeds & Northrup Type K Potentiometer. The distance between the knife edges was accurately adjusted, and was kept constant for all observations.

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AFTER the density of the original wires had been measured, by weighing in water and in air, their cross-sectional areas were determined. The area was then calculated from the volume thus determined and the length of the wire. These areas were checked by measuring the diameters both with a micrometer caliper and with a micrometer microscope under a magnification of 70 diameters, and were found to agree

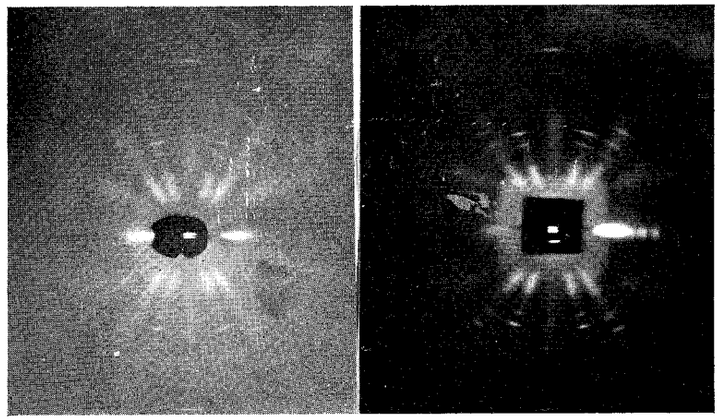

Fig. 5.

a. Rotation Spectrum of Core. b. Oscillation Spectrum.

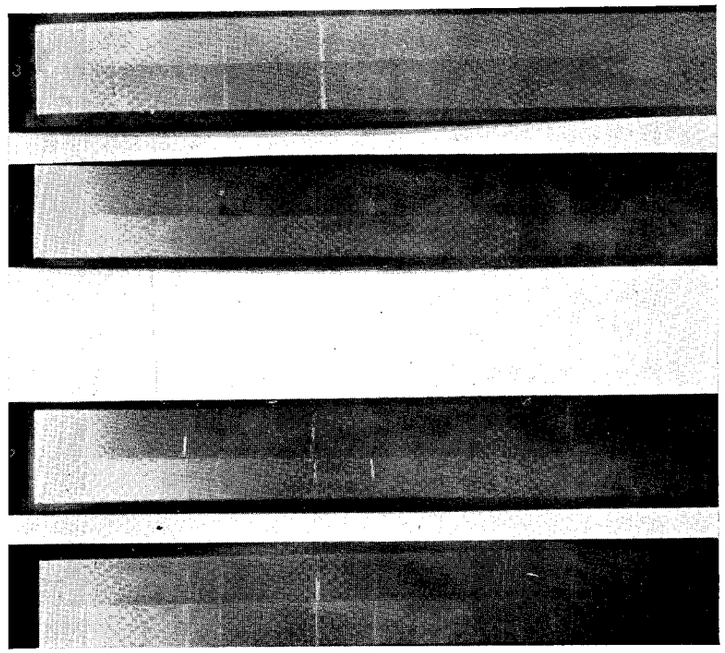

Fig. 6. 10. No. 6 B. and S. Annealed Copper Wire.
11. No. 6 B. and S. Annealed Copper Wire, Etched to 0.5 mm. Diameter.
12. Same as 11, Rotated 90°.

within the necessary limits of accuracy. For the intermediate samples, where differential etching might occur along the length of the wires, the micrometer measurements were carefully checked. As an added precaution, after the last potentiometric measurement was made the wire was cut under the knife edges, and the cross-sectional area of that part of the wire actually measured was again determined by all three methods mentioned above. The results so obtained were all in agreement.

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TABLE II summarizes the results of these measurements for the wires chosen as representative. Fig. 8 is a graphical representation of these results plotted logarithmically so as to represent more closely the cumulative nature of the changes in the resistivity observed.

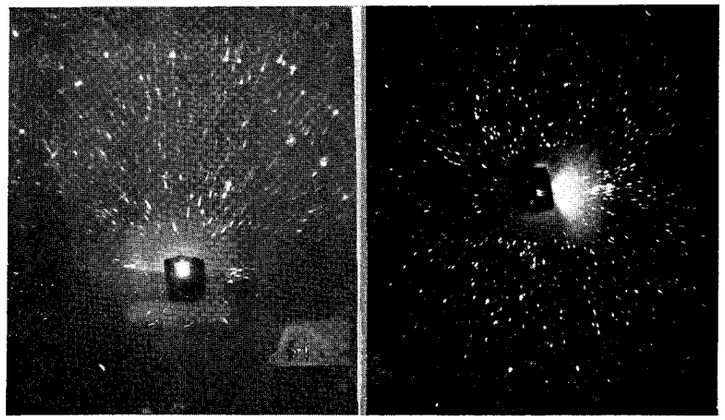
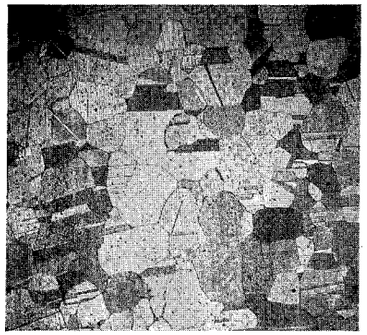


Fig. 7—a. Spectrum of Surface of H. D. Wire Annealed above 1050°C. ✦ b. Spectrum of Core of H. D. Wire Annealed above 1050°C. ✦ ✦



c. Micrograph of Core of H. D. Wire Annealed above 1050°C. (100-X). ✦ ✦ ✦

THE resistivity in the skin in hard-drawn wires was found to be higher than in the wires after the first etching. More correctly stated, the average resistivities of the original wires were higher than the average resistivities for the wires after the outer surfaces had been dissolved off. However, for the hard-drawn wires the curves representing these average resistivities changed abruptly in slope after the first etching, and upon subsequent etchings rose to a maximum value as the longitudinal axes of the wires were approached. For finer wires, where it was thought that the small current flow might have had some heating effect which would increase the resistivity, the probable rise in temperature occurring in the wire (assuming no radiation) was calculated for the time necessary to make an observation. It was found that the increase in temper-

TABLE II—Change in Specific Resistivity With Cross-Sectional Area

Wire B. & S. Gauge	Area at Section (Sq. cm.)	Specific Resistivity (Microhms cu.cm.)
No. 12 H. D.	0.0333	1.764
	0.0314	1.762
	0.00255	1.808
	0.00149	1.819
	0.00129	1.914
No. 6 H. D.	0.1350	1.762
	0.1323	1.738
	0.0782	7.781
	0.0349	1.775
	0.0151	1.789
	0.0052	1.797
	0.00172	1.841
No. 6 Annealed	0.1350	1.728
	0.1320	1.721
	0.0775	1.726
	0.0378	1.712
	0.0172	1.736
	0.00371	1.727
	0.00135	1.729
No. 10 H. D. (from native Cu)	0.0557	1.729
	0.0529	1.698
	0.0137	1.745
	0.00288	1.793
	0.00135	1.840
No. 10 H. D. (Same as No. 10 above—annealed)	0.0555	1.683
	0.0132	1.628
	0.00295	1.682
	0.00141	1.725

ature would be negligible for the currents used. However, to check the specific resistivity in these finer wires, various current strengths were used and the drop in potential in the wire was determined for each. The results shown in the foregoing curves were obtained by using currents of sufficiently low strength that the heating effect manifested was negligible.

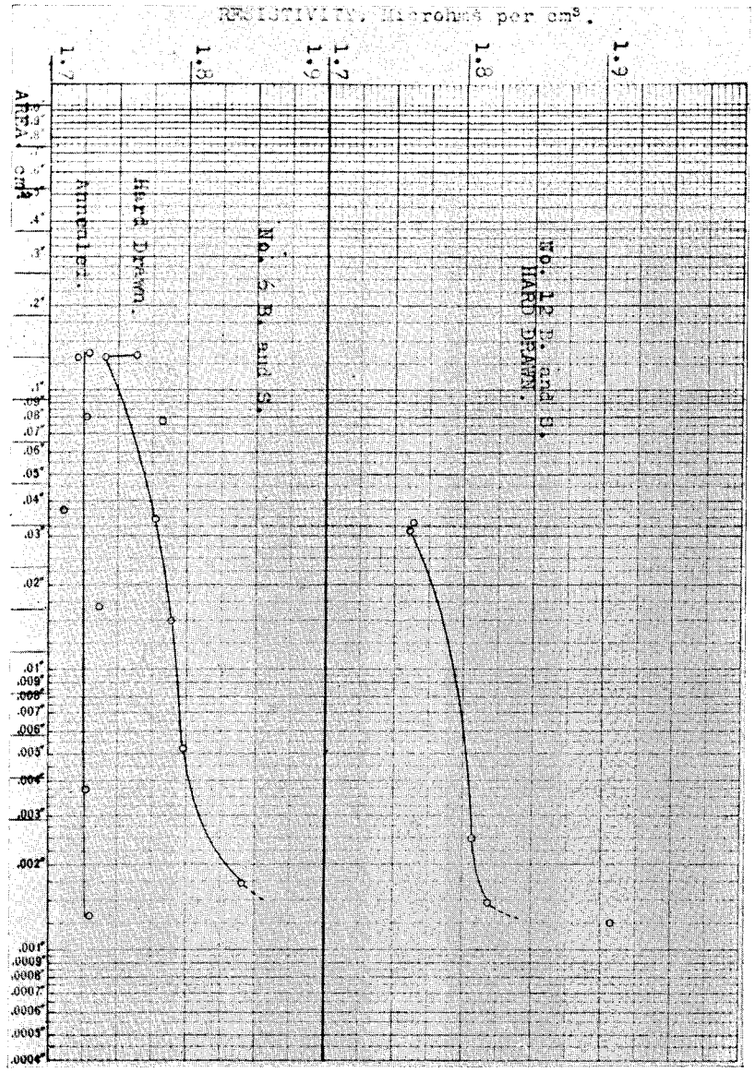


Fig. 8—Curves Correlating Resistivity Changes with Changes in Cross-Sectional Area of Hard-Drawn Copper Wire.

✦ ✦ ✦ ✦ ✦ ✦ ✦

Resistance to Deformation Correlated with Cell Orientation and Other Concepts

NADAI [10], in his treatment of plasticity, states that one property of the flow or slip of layers has an especial bearing on the mechanics of the plastic state. The planes of the thin slip layers in which the metal is apparently more severely deformed than elsewhere coincide approximately with the two planes of principal shearing stress. In the case of tension the angle which the slip layers make with the axis of the test piece is usually about 47°, a little greater than the angle in a compression test piece—45°. In copper crystals, the octahedron planes act as slip planes, and the edges of the octahedron represent the direction of the slip. The 100 planes are the planes of second easiest slip. [11]

✦ ✦ ✦

THE X-ray spectra obtained indicated that two orientations were present in the core: one with the cube diagonal, 111, in the core of the wire, and the other with the cube edge, 100, in the core. The prevalence and the relative intensities of the spots in the spectral pattern indicated that the 111 orientation occurred about twice as frequently as the 100.

✦ ✦ ✦

IN a cube the 111 faces form an octahedron. When the cubes (unit cells) are so oriented that the 111 direction is in the core of the wire, one set of 111 planes is perpendicular to the deforming force and the other three sets make 18°-25′ with the tension. The 100 planes make an angle of 35°-14′ with the drawing force.

✦ ✦ ✦

THE 111 planes in the face-centered cubic cell are those of easiest slip: the atoms on these planes are closer together than on any other, and for face-centered cubic symmetry the planes themselves are planes of greatest interplanar distance. When copper is cold-drawn into wire the planes of easiest slip and of second easiest slip are so oriented that they make angles with the deforming force which are very unfavorable to slipping. Such reduction of slip possibility means an increase in the tensile strength, a conclusion which is in exact accord with the orientation tensile strength findings of Harris. [12] A consideration of the preferred orientations in cold-drawn wires of aluminum and silver, and of the relative tensile strength increase of cold-drawn wire over that of the cast or annealed metal, also corroborates this conclusion.

✦ ✦ ✦

SCHMIDT and Wasserman [13] state that aluminum when cold-drawn is oriented with only the 111 direction in the wire axis, a fact which would indicate a large relative increase in tensile strength. On the other hand the unit cells of cold-drawn silver wire are oriented, as is copper, with both the 111 and the 100 directions in the wire axis, but the 100 are three times as numerous as the

111. Cold-drawn copper is between the two, with 60 per cent of the 111 and 40 per cent of the 100. The 100 orientation is one which is very advantageous for drawing inasmuch as it so places the 111 planes that they make a 45° angle with the pulling force—the condition for maximum ease of slip. Hence it might be concluded that the relative change in tensile strength in wires would vary directly with the per cent 111 orientation and inversely with the 100 orientation. This is shown to be true in the case of copper, silver, and aluminum. From the annealed to the cold-drawn state, aluminum increases in strength about 3 times, copper about 2.4 times, and silver about 2 times. (Table III). This is for the total wire, about half of whose diameter is core, preferredly oriented, the other half being randomly oriented.

crystalline and that fractures are usually intra-crystalline rather than inter-crystalline. To be harder means that the atomic attraction forces are greater than the repulsion forces. If one accepts Coulomb's inverse square law of attraction, and also the hypothesis that the repulsion varies inversely as some higher power of the internuclear distance, the foregoing findings as to hardness mean that the nuclei are closer together.

✦ ✦ ✦

DENSITY measurements, obtained by the Pyknometer Bottle Method and corrected for atmospheric conditions, indicate that in both hard-drawn Lake copper and hard-drawn electrolytic copper the density of the core is greater than that of the outer mantle. Both these densities are less than the density of the annealed wire. (Table IV). Apparently the mechanism of slip on

TABLE III

Tensile Strength

Metal	111	100	Annealed	H. D.	% increase
Silver	25%	75%	21,000	40,000	100
Copper	50%	50%	31,000	72,000	140
Aluminum	100%	0%	10,000	30,000	200

ANOTHER possible factor which may enter into the problem is disorganized material on the slip-planes which is due to slip. Whether this be truly amorphous or exceedingly finely crystalline material (crystal fragments) the facts are that below the equicohesive temperature this disorganized material is harder than the truly

slip-planes is different from that which orients the cells in the grains in the core. One possible explanation is that in some manner the lattice discontinuities which are caused by slip are filled with a denser, disarranged, amorphous, or fragmental material. The equicohesive temperature might be considered to be the one at

which the atoms attain enough mobility to regain their equilibrium between the forces of nuclear attraction and repulsion.

✦ ✦ ✦

TABLE IV

Density of Copper Wire

Average Density of Hard Drawn Wire
8.8430
8.8435
8.8433
———
8.8433 Average

Density of Core of Hard Drawn Wire
8.8588
8.8563
8.8510
8.8492
8.8512
8.8518
———
8.8525 Average

Density of Whole Wire Annealed at Cherry Red Heat in Assay Muffle
8.8559
8.8683
8.8640
8.8604
———
8.8621 Average

Density of Whole Copper Wire Annealed at From 1050°C to Near the Melting Point. The Wire Softened in Some Places.
8.8656
8.8609
8.8691
8.8688
8.8653
8.8607
8.8689
8.8686
———
8.8659 Average

The Above Measurements Are All From Sections of the Same Wire.

THE microscopic examinations of cross-section, both vertical and longitudinal, of the hard-drawn copper wire, show practically no variation in grain size from surface to core, but Rockwell tests show quite a large variation in hardness (Table V). The hardnesses were taken of both cross and longitudinal sections. For the longitudinal section the wire was bent along a long radius curve, and the outside of the curved section was then polished off until the center of the core was exposed. Since hardnesses were taken along the polished section, a thorough survey of the material from core to surface was possible. Hardnesses were also taken across the shorter dimension of the polished surface, on end sections of pieces of wire, and along the middle of the core of pieces of sections which had not been bent. The results all showed that the core zone of the wire was the hardest portion.

✦ ✦ ✦

BECAUSE grain size did not vary from the surface to the core and because the hardness did vary and was greater in the core zone, hardness and tensile strength must be due to other factors than small-grain slip-interference. This conclusion is particularly well illustrated by the hardnesses along the long direction of the polished surface. Inasmuch as the core orientation is one which permits the unit cell to assume any position in 360° of azimuthal rotation around the 111 and the 100 axes, there is a greater possibility for the 111 and the 100 planes to make a 45° angle with the deforming force in the core than in the rest of the wire. A proof of this condi-

tion is that the longitudinal hardness of the core was greater than the core hardness at 90° to the core axis. This would seem to show that even though grain refinement and preferred orientation are eliminated from the equation, there is still something which causes an increased hardness—quite possibly a state of unstable equilibrium in which the forces of attraction are greater than normal. This condition in turn might well be due to the presence of a crystallographically disorganized material—amorphous or crystal fragmental.

✦ ✦ ✦

RECENT work with electron diffraction from polished metallic surfaces[14] shows that the surface material is in a "semi-orderly" condition. The diffraction pattern is very similar to that of liquids. French[14] found that the broad diffraction rings in the electron spectra of a polished copper surface were indicative of atomic spacings which differed from the atomic spacings in the crystalline state.

✦ ✦ ✦

IT is agreed that grain refinement causes slip interference, but grain refinement brings another possibility into the problem. Maximum ease of slip should exist when the planes of easiest slip make a 45° angle with the deforming force. It is easily seen that if a specimen containing 100 grains randomly oriented is broken up into 1000 grains, again randomly oriented, the probability is 10 times greater that there will be grains in optimum position for easy slip than in the original sample; therefore deformation should be easier and should tend to overcome the keying effect of smaller grains. This is a supposititious case in which no preferred orientation results from the grain refinement.

✦ ✦ ✦

IF, however, preferred orientation does result, as happens in the case of cold-drawn copper wire, and if it is one which opposes easy slip, its action and that of keying are additive.

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Conclusions

THE foregoing experiments show that copper, though an isometric metal, is not isotropic. The increase in hardness and the increase in tensile strength of cold-drawn copper wire are shown to be not only effects of small-grain slip-interference but also functions of unit-cell orientation and to be due to the probable presence of another phase of an amorphous (crystal fragmental) condition.

✦ ✦ ✦

Electrical Conductivity and Cell Orientation

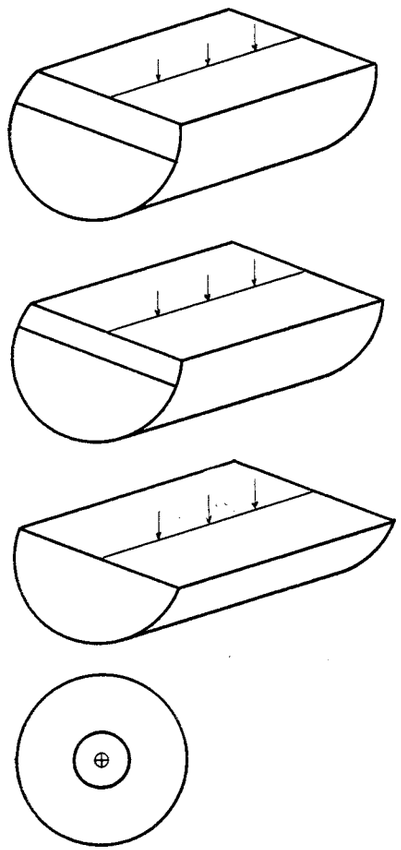
THE X-ray spectra showed a thin skin of preferredly oriented material on the outside of the wire, then a layer of randomly oriented grain, and then the core of preferredly oriented material. The diameter of the core was about one-half the total diameter of the wire. The orientation of the unit cells in the core and in the skin was the same. The specific resistivity of the skin was found to be greater than that of the randomly oriented material just beneath, and this specific resistivity increased as more and more of the wire was etched off and as, ipso facto, the core was approached.

✦ ✦ ✦

AN analytical consideration of the planar orientation in the core of the cold-drawn wire shows that one set of 111 planes is perpendicular to the longitudinal axis and that at least 60 percent of the orientation is one with 111 planes in the cross-section of the wire, the other 40 per cent being one with 100 planes at right angles to the core.

TABLE V

HARDNESS OF HARD-DRAWN COPPER WIRE



51.5			
52.0			
51.0			
51.0			
54.0			
51.5			
			51.8 Av.
47.5			
56.5			
53.0			
53.0			
49.5			
			51.9 Av.
52.5	57		
53.0	53		
57.5	55		
50.0	54.5		
51.0	54		
56.0	54.5		
53.5	53		
			53.9 Av.
59.5	56	51	
50.0	51	57	
57.5	57	60	
50.0	56	57	
59.0	51	57	
52.0	61	52	
			56.3 Av.

ISOTROPIC crystals have like properties in all directions. Dana[16] emphasizes the fact that such crystals are not isotropic with reference to those properties which depend upon molecular structure alone, such as cohesion and elasticity; to these can be added thermal conductivity and (by analogy) electrical conductivity. Davey[15] found variations in electrical conductivity along different directions in a copper crystal.

✦ ✦ ✦

HUDSON[17] states that the outermost, or valency, electrons in atoms are the electrical conductors. The orbits of these outermost electrons may actually intersect, and in certain positions the nuclear attraction for an electron may be neutralized by the attraction of the nuclei of other atoms, the change from neutral to charged state occurring as often as 40,000,000 times per second. The space between the atoms is thus filled with detached, or free, electrons forming an electronic gas. These free electrons move about in a manner similar to molecules. Their motion will be interrupted or affected by collision or by nuclear attractions. There will be no tendency for them to move very far from their origin, because each electron is continually pulled back into its original orbit or that of an adjacent atom, a phenomenon which will be discussed later in correlating the conductivity with the space lattice. Hudson further states that the conductivity of a solid depends upon the space density and the freedom of the electrons in the electronic gas which fill the space between the orderly rows of atoms. If an electric potential is maintained between any two planes in any solid, the free electrons not only have a random and rapid thermal velocity but also are given a small drift velocity in a common direction. This drift velocity constitutes an electric current.

✦ ✦ ✦

THUS the conductivity depends upon the space density of the free electrons and upon the mean free path for each electron. This path is affected not only by collisions but also by the nuclear attractions of the vibrating atoms in the solid.

✦ ✦ ✦

THE octahedral planes have the greatest number of atoms per unit area, and consequently, exert a greater amount of attraction for the free electrons per unit area than does any other plane in face-

TABLE VI

Plane	Relative Nearest Distance of Approach of Atoms	Relative Interplanar Distance	Relative Atomic Dist. From Plane to Plane	Rel. Average Interatomic Dist. in Plane
111	0.707	0.577	0.707	0.707
(100) (2)	0.707	0.500	0.707	0.854
(110) (2)	0.707	0.353	0.707	1.038

centered cubic symmetry. The octahedral planes have also the greatest interplanar distance — a greater distance to "drift" the free electrons than that of any of the crystallographic planes.

✦ ✦ ✦

IN other words, if the attraction per unit area of atomic plane varies as the density of atomic population, the 111 plane will have a greater attraction for the free electrons of the electronic gas than will the 100 planes, which have a lower atomic density and will therefore have less attraction for the free electrons.

✦ ✦ ✦

THE average relative interatomic distance in the 111 planes is 0.707. (The edge of the unit cell is taken as unity). The average relative interatomic distance in the 100 planes is 0.854, and that of the 110 planes is 1.038.

✦ ✦ ✦

IT is not known whether Coulomb's inverse square law of attraction is valid at such small distances, but until proved invalid, it will be accepted as true.[35]

✦ ✦ ✦

FROM this law it is possible to conclude that both the interatomic distance and the interplanar distance affect the drift of free electrons. In the first place, it is reasonable to suppose that the planar attraction for the electrons varies inversely as the square of the average interatomic distance in the plane. Hence the relative planar attraction of the 111, 100, and the 110 planes would be as:

$$\frac{1}{(0.707)^2} : \frac{1}{(0.854)^2} : \frac{1}{(1.038)^2}$$

or as 2 : 1.37 : 0.93. In the second place, if these three series of planes had equal interplanar distances, it would be more than twice as difficult to cause a free electron to "drift" from one 111 to the next 111 plane as to cause it to "drift" between two adjacent 110 planes. But these three series of planes do not have equal interplanar distances; instead, the relative interplanar distances are as 0.577 (111) : 0.500 (100) : 0.353 (110). This ratio would also affect the interplanar flow of free electrons. Again the inverse square law very probably would hold. If the planar attractions for the free electrons were the same for the 100, 110, and the 111 planes, the probabilities of the electron flow between the various planes would be inversely as the square of their interplanar distances.

$$\begin{array}{ccccc} 111 & & 100 & & 110 \\ \frac{1}{(0.577)^2} & : & \frac{1}{(0.5)^2} & : & \frac{1}{(0.353)^2} \end{array}$$

$$:: 3 : 4 : 8$$

✦ ✦ ✦

THEREFORE if these relative planar attractions are taken into consideration the relative probabilities of the free electrons "drifting" between the 111 planes, between the 100 planes, and be-

tween the 110 planes can be computed as being:

111	100	110
3	4	8
2	1.37	0.93

or

1 : 2 : 6

✦ ✦ ✦

TO conduct electricity along a wire the free electrons must pass through the 111 planes, one set of which is perpendicular to the wire axis; this set is the most densely populated of the atomic planes. It is easily seen that an electron is less likely to pass through such a plane than through a more sparsely populated one.

✦ ✦ ✦

THE orientation in the core is a directional one; this of course means also a planar orientation—that is, one set of the 111 planes is perpendicular to the wire axis; but though there is a planar orientation there is nothing which indicates that the planes are so aligned as to result in perfect articulation. In fact, the arrangement is more likely to be a staggered one, which could further interfere with the passage of free electrons.

✦ ✦ ✦

THE probability that the deformation mechanism caused unit cells or small blocks of unit cells to preferredly orient themselves within the grains makes it likely that the core has much more intercellular or intercrystalline material than has the outer mantle. Hume-Rothery[19] says that "any conductivity measurements on polycrystalline metal involve the resistance of the intercrystalline material as well as that of the crystals themselves."

✦ ✦ ✦

Conclusions

ELECTRICAL conductivity is thus shown to be a function of cell orientation, and the cell orientation in the core of hard-drawn copper wire is shown to be one whose effects are adverse to the most efficient electrical conductivity.

✦ ✦ ✦

Electrical Conductivity of Copper Wire Drawn in Various Ways

MODERN metallurgical research has made exceedingly great progress in the study and utilization of the possibility of improving the various properties of metals and alloys. Strength, reduction of weight per unit of strength, hardness, and resistance to fatigue, corrosion, and heat have all been the subject of much thought and experiment, with beneficial results.

✦ ✦ ✦

ALTHOUGH electrical conductivity has not been greatly improved, the conductivity of copper has in certain instances been increased somewhat by a more efficient removal of impurities, both in the smelting[20] and electrolytic processes.

✦ ✦ ✦

IT has been shown that the cold-drawing of copper wire continuously in one direction results in a certain fiber type of preferred orientation of the unit cells and

that this type of orientation reduces the conductivity from that of an annealed wire, whose unit cells are more randomly oriented. It has been shown also that the conductivity of cold-drawn copper wire decreases toward the core of the wire and that the degree of such preferred orientation increases as the core is approached.

✦ ✦ ✦

RESEARCH was undertaken in order to determine which methods of wire drawing would result in different types of preferred orientation and possibly in an improvement in conductivity. Though copper is isometric it was hoped that some such condition might exist as does in calcite and quartz, in which the electrical conductivity in the direction of the main axis is exceedingly greater than in a direction perpendicular to it.[21]

✦ ✦ ✦

A SECTION about 8 in. long was cut from a commercial wire bar. This was machined to a square cross-section to eliminate any effects which might be due to surface conditions resulting from casting. The block was then cut into sections approximately ¾ by ¾ by 8 in., twenty such pieces being obtained from the block (Fig. 9). Each section was rolled to a size proper for drawing, and the entire section was drawn through one die and then cut into four pieces. These four pieces were then so drawn that from each section were obtained four wires, cold-drawn through 8 passes (8 dies) to No. 8 B. & S., with the following difference in drawing direction:

1. Continuous drawing through 8 dies.
2. Reversal of direction after each pass.
3. Reversal of direction after every other pass.
4. Reversal of direction after every fourth pass.

As a result of this technique, wires representative of the different methods of drawing were also representative of the entire cross-section of the wire bar. A slab ¾ in. thick was taken from the same

1	2	5	6	9	10	13	14
3	4	7	8	11	12	15	16
29	30	25	26	21	22	17	18
31	32	27	28	23	24	19	20
33	34	37	38	41	42	45	46
35	36	39	40	43	44	47	48
61	62	57	58	53	54	49	50
63	64	59	60	55	56	51	52
65	66	69	70	73	74	77	78
67	68	71	72	75	76	79	80

Fig. 9. Section of Wire Bar Showing Numbers of the Wires and Section of the Bar from Which the Wires Were Drawn. ✦ ✦ ✦

wire bar; after the casting surfaces were planed off, it was cut into sections which were parallel to the top of the bar. These sections were then drawn in a manner similar to that explained above, merely to determine whether any anisotropy existed between the longitudinal direction and a direction at right angles to the long axis of the bar. No anisotropic condition was found which varied the final conductivity. The wire bar from which the section was taken had the following analysis:

Copper plus silver—99.930%
Silver—32.2 oz. per ton

✦ ✦ ✦

X-RAY spectroscopic examinations were made of wires representative of each type of drawing. Different parts of the wires were examined by successively etching off layers, each etching followed by a raying. In this manner it was possible to determine the type and degree of preferred orientation existing in any portion of the wire from the surface to the core. (Greenwood[22] in differentiating the degree of orientation with depth, used not only successive etchings but also radiations of different penetrations.) Successive Hull-Debye-Shearer spectra were obtained until the wires were approximately 0.2 mm. in diameter. Pinhole spectra were next obtained, first with the wire stationary and then with it rotating. Molybdenum radiation (30 KV) was used; the Hull spectra were obtained on a General Electric Diffraction Unit, and pinhole spectra were obtained on Pye and Hilger-Muller spectrographs.

✦ ✦ ✦

SPECTRA of the surface of the wires showed a thin skin of preferredly oriented material inside of which was material with a random orientation that developed more and more into a fiber type of orientation as the core was approached. The spectra were symmetrical, both horizontally and vertically; the obvious inference is that the preferred direction, which would naturally be in the direction of drawing, was perpendicular to the X-ray beam. Evidence of the absence of perfect orientation was given by the almond-like shape of the spots, which formed almost complete circles.

✦ ✦ ✦

THE spectra of the wires revealed no difference in the cell orientation which could be considered as due to difference in methods of drawing. The preferred orientation was of two types, one in which the cube diagonal, 111, was in the axis of the wire and the other in which the cube edge, 100, was in the axis. Because of predominance of the spots which coincided with the theoretical locations of reflections due to an orientation with the 111 direction in the fiber axis, it was estimated that in the wires examined the 111 orientation was twice as prevalent as the 100. Because of the mechanism of deformation, perfect parallelism of the preferred direction is the hypothetical ideal. The deforming force really orients the preferred direction conically, the

TABLE VII

Wire No.	Conductivity Wire continuously drawn through eight passes	Wire No.	Conductivity Direction of drawing reversed after each pass	Wire No.	Conductivity Direction of drawing reversed after every other pass	Wire No.	Conductivity Direction of drawing reversed after each four passes
1	96.30	2	96.15	3	96.15	4	96.15
5	97.25	6	96.40	7	96.40	8	96.15
9	96.25	10	96.00	11	96.40	12	96.35
13	96.05	14	96.35	15	96.20	16	96.05
17	96.50	18	96.25	19	96.20	20	96.40
21	96.30	22	96.30	23	96.20	24	96.45
25	96.30	26	96.25	27	96.30	28	96.30
29	96.40	30	96.00	31	96.25	32	96.30
33	96.60	34	96.15	35	96.10	36	96.20
37	96.40	38	95.95	39	96.30	40	96.35
41	96.50	42	96.05	43	96.20	44	96.20
45	96.45	46	96.15	47	96.30	48	96.40
49	96.60	50	96.50	51	96.20	52	96.35
53	96.20	54	96.40	55	96.40	56	96.20
57	96.50	58	96.05	59	96.10	60	96.35
61	96.40	62	96.25	63	96.35	64	96.25
65	96.30	66	96.05	67	95.90	68	96.30
69	96.20	70	96.65	71	96.35	72	96.45
73	96.65	74	96.30	75	96.50	76	96.45
77	96.85	78	96.70	79	96.60	80	96.20
	Average 96.45		Average 96.25		Average 96.27		Average 96.29

sides of the cone very closely approaching the axis, which is the axis of the wire. Apparently, the process involved in this type of plastic deformation is irreversible; that is, work applied in the opposite direction is unable to restore the initial state.

✦ ✦ ✦

UPON consideration of the conditions involved, the similarity of the spectra of the wires drawn in different manners is easily understood. Copper is isometric, and both the 111 and the 100 directions are axes of symmetry. The only effect of reversing the drawing direction on either of the two orientations would be merely to reduce the conicalness of the orientation or to effect a double-pointed-cone type of cell arrangement. Hence it might be concluded that, because of the great similarity of orientation, the conductivities would be approximately the same. This was found to be the case.

✦ ✦ ✦

THE conductivities varied within each type of drawing as well as between types (Table VII). The average conductivities indicated that the more frequent the reversal of drawing direction the lower the conductivity. The eight passes, all in one direction, lowered the conductivity to 96.45%; four reversals in the eight passes lowered it to 96.25%; and reversing after every other pass and after every fourth pass lowered it to 96.27% and 96.29% respectively. There was no appreciable variation in the tensile strengths of the different wires.

AFTER being tested for conductivity the wires were annealed, and the conductivities were redetermined. The different methods of drawing did not affect the conductivity of the annealed wires.

✦ ✦ ✦

Conclusion

REVERSAL of the direction of drawing during the process of cold-drawing copper wire causes a slight decrease in the electrical conductivity, but does not appreciably alter the cell orientation.

✦ ✦ ✦

Summary

COLD-DRAWING of copper wire is shown to cause a definite type of preferred orientation of unit cells in the core. This orientation is such that the 111 and the 100 planes, which are the planes of easiest slip in face-centered cubic lattices, are in positions which militate against optimum ease of deformation. Deformation by shearing takes place easiest when the planes of easiest slip make an angle of 45° with the deforming force. The cell orientation at the core causes this angle to vary widely from the optimum. Micrographs and directional properties corroborate this conclusion.

✦ ✦ ✦

THIS cell orientation has an effect on the electrical conductivity also. Conductivity is a function of the "drifting" of free electrons by an impressed electromotive force. The core orientation places the most densely populated atomic planes directly across the path of drift, and too these planes have the greatest interplanar distance for this type of symmetry. A greater possibility for staggered planes is added to these two conditions and from the three is developed a theory for the increased electrical resistivity of the core of cold-drawn wire.

✦ ✦ ✦

SAMPLES of wire were drawn with various combinations of reversal of drawing direction. The electrical conductivity of wires drawn in the straight-forward method was slightly higher than the conductivity of wires whose drawing directions had been reversed. The tensile strength was not noticeably affected by such reversal.

Acknowledgements

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✦ ✦ ✦

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