Photomicrography and Technical Microscopy in Its Application to Telephone Apparatus

By FRANCIS F. LUCAS

NOTE—The following paper may be considered as introductory to the subject of photomicrography. Doubtless everyone is casually familiar with photomicrographs of the crystalline structure of various metals. The application of this branch of the optical art to the study of metals is very important in the design and manufacture of telephone apparatus but its importance in telephony is more far-reaching than in the study of metals alone. Various of these applications are suggested by the illustrations reproduced in the Appendix of this article.—*Editor.*

INTRODUCTION

BY photomicrography is meant the adaptation of photography to microscopy, or the art of photographing a magnified image. The scope of the art embraces the reproduction of images ranging from natural size up to magnifications of several thousand times, the degree of magnification being expressed in terms of diameters. It will be seen that the image is not always magnified but in some instances may be at a 1:1 ratio or when large subjects are being photographed, at an actual reduction in size. Such low-power work is often spoken of as gross photography but so far as the equipment and technique of treatment is concerned it is low-power work.

Low-power work may be considered as treating with magnitudes from 1 to about 30 diameters. Medium-power work deals with magnifications from about 30 to about 500 diameters, and high-power work extends from 500 diameters upward. The limit of useful magnification is a much disputed question. It is sometimes contended that 1,500 diameters represents about all that is worth while, but the fact that very few pictures are published which exceed 1,500 diameters in magnification would lead to the conclusion that either the limit is from 1,000 to 1,500 or else the art has not been developed to the state where substantial gains result by going higher. This matter will be considered at greater length below.

GENERAL DISCUSSION OF APPARATUS

The reason that photomicrography is grouped under three classifications according to magnification, is because the apparatus used in each case is quite different and because the preparation of the subject and its treatment also differ. In fact for low-power work the microscope often may be dispensed with entirely, the lens being secured directly to the camera; in other cases, the microscope serves only as a

convenient support for a lens. In the treatment of most transparent mounts an illuminating device termed a substage condenser is necessary, the microscope then forms a very necessary adjunct to low-power work.

Medium-power work always requires the use of a microscope, and because rigidity in mounting and accuracy in adjustment are very necessary to correct rendering of the image, some sort of a stand is provided on which the microscope and a suitable illuminating train are mounted. Usually this stand takes the form of a narrow wooden or metal table supported by substantial metal legs. The table carries an optical bench which in practice is a metal bar or rail of special and rugged construction upon which the optical parts, the illuminant and the camera are mounted and are capable of adjustment so that they may be aligned optically. The description necessarily, meets generalized conditions. There is, however, a great similarity in the product of different makes of equipment and they all follow the same conventional lines, improvements in one make quite often being met by similar changes on the part of other makers.

There is no very well defined line between medium-power and high-power apparatus so far as the stands are concerned, but when it comes to real precision apparatus the choice in equipment is limited to possibly two or three makes. The difference is to be found in the quality of the optical parts and in the general stability of the assembly. A skilled technician may produce remarkable medium-power results with quite ordinary apparatus but no amount of training and skill can make good in high-power work for the actual shortcomings of an objective. Given a really good objective the skilled operator may use an inferior type of stand and secure very fine results, but he will be working under a considerable handicap and his work will not be consistently good because lack of the right sort of apparatus is apt to introduce variations in illumination, focusing, or adjustments which will prove ruinous to good definition.

Thus far consideration has been given to apparatus capable of yielding a magnified image of some tangible sort of a specimen, but there is an entirely different form of microscopic equipment which reveals the presence of particles beyond reach by all other known means of microscopic vision; reference is made to the ultra-microscope. This instrument is not ordinarily provided with photographic apparatus although with certain classes of work and under favorable conditions it is possible to reproduce the image photographically. Both liquids and solids may be studied by this means but in each case the specimen must be capable of transmitting light.

The Compound Microscope

It is obvious that a complete technical discussion of the instrument and equipment used in photomicrography is not within the scope of this paper nor would it be of interest to many readers. In order to appreciate the possibilities of technical microscopy as an aid in the

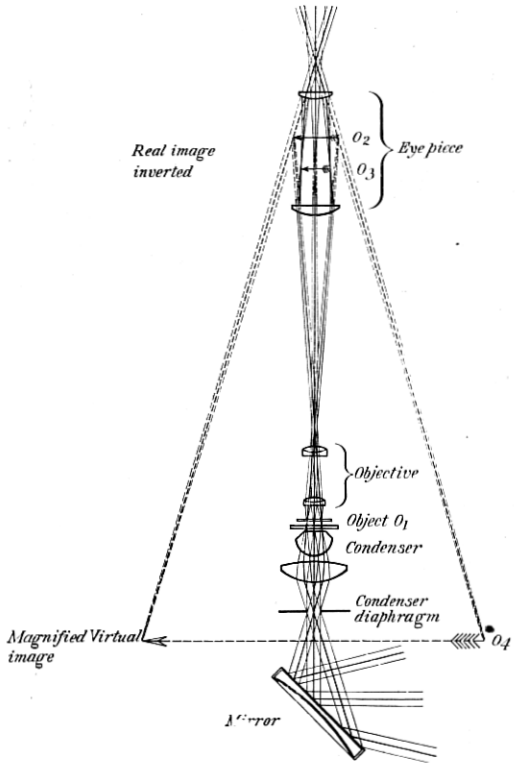


Fig. 1—Optical Diagram of the Compound Microscope.

solution of definite engineering problems relating to telephone apparatus it is necessary, however, to consider more in detail the equipment used.

The optical system of the compound microscope is shown diagrammatically in Fig. 1, and in Figs. 2 and 3 are pictured two modern representative research type microscopes. In the diagram three parallel pencils of light are shown reflected upward into the condenser which by proper focusing is caused to illuminate a transparent object (suitably prepared and mounted as described later) placed in position on the microscope stage. As shown the objective would form

an inverted real image of the object O_1 at O_2 but the rays are intercepted by the lower lens of the eyepiece before the real image is formed. The lower eyepiece lens in combination with the upper

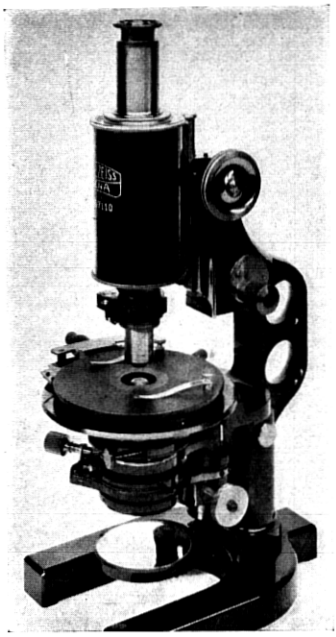


Fig. 2—Research type of microscope by Zeiss. Large barrel for photo-micrography; revolving mechanical stage, and sliding objective changers.

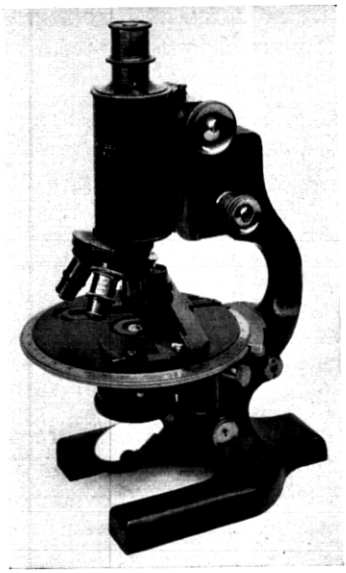


Fig. 3—Research type of microscope by Spencer Lens Co. Large barrel for photo-micrography; a large revolving stage with graduated circle, and a removable mechanical stage.

eyepiece lens forms a magnified virtual image O_4 of the real image O_2. There are two magnifications of the object and the resulting final magnification is the product of the magnifying powers of the objective and the eyepiece.

It should be noted that the objective produces an enlarged image of the object and that the eyepiece further magnifies this image; from this it is evident that if detail is lacking or if the image is not a good likeness of the object, the eyepiece will not make up for the shortcomings of the objective. The objective, then, becomes perhaps the most important part of the whole outfit. No one objective will serve for all purposes because of the limited range throughout which each particular objective is most useful; hence it is necessary to have a whole battery available so that the objective may be selected to suit the requirements of the work.

Objectives are divided into four general classes: achromatic, semi-apochromatic, apochromatic and monochromatic for use with ultra-violet light. These objectives do not consist of single lenses but are composed of two or more lenses very accurately centered and permanently mounted in a metal holder. The component parts of the lens system are chosen with regard to their ability to correct or compensate

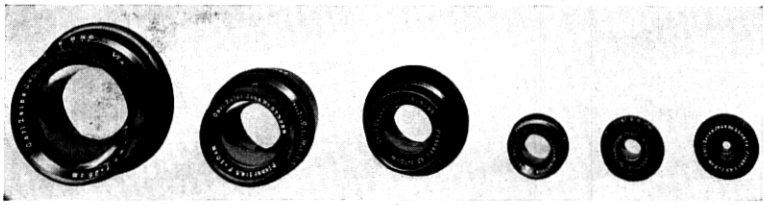


Fig. 4—A battery of low-power lenses. These lenses are used without eyepieces. Each lens is equipped with a diaphragm for stopping the aperture.

for certain errors which are always characteristic of a simple lens. The value of an objective depends on the degree to which these imperfections have been overcome.

The difference in quality between the first three classes of objectives is primarily a matter of correction for chromatic and spherical aberrations. Chromatic aberration is the inability of a lens to focus sharply at the same point the different colors which go to make up the incident light and the inability to bring two rays of incident light of the same color to the same focus is termed spherical aberration.

The achromatic objectives have the chief optical defects corrected in a sufficient degree for the physiologically most effective rays (yellow-green) of the visible spectrum, while in the case of the apochromatic objectives the correction of the image defects extends approximately evenly over the entire range of the visible spectrum from the red to the violet regions.

In the achromatic lenses the fusion of the chromatic rays becomes less and less complete for rays belonging to the extremes of the visible spectrum under the ordinary conditions of illumination with white light, and this imperfection becomes more apparent when highly magnifying eyepieces are used. There are also residual imperfections in the fusion of the rays so that the colors of objects are not rendered with absolute precision in their finer shades. In the apochromatic objectives the fusion of the rays is so perfect that they may be used in conjunction with high-power eyepieces, and because of this perfect fusion the natural colors of the object are rendered with

great precision. The semi-apochromatic objectives contain fluorite elements and these objectives occupy a position in quality intermediate between the achromatic and apochromatic types.

Objectives are classified and listed according to their optical characteristics such as primary magnification, numerical aperture and focal length and as to whether they belong to the "dry" or the "im-

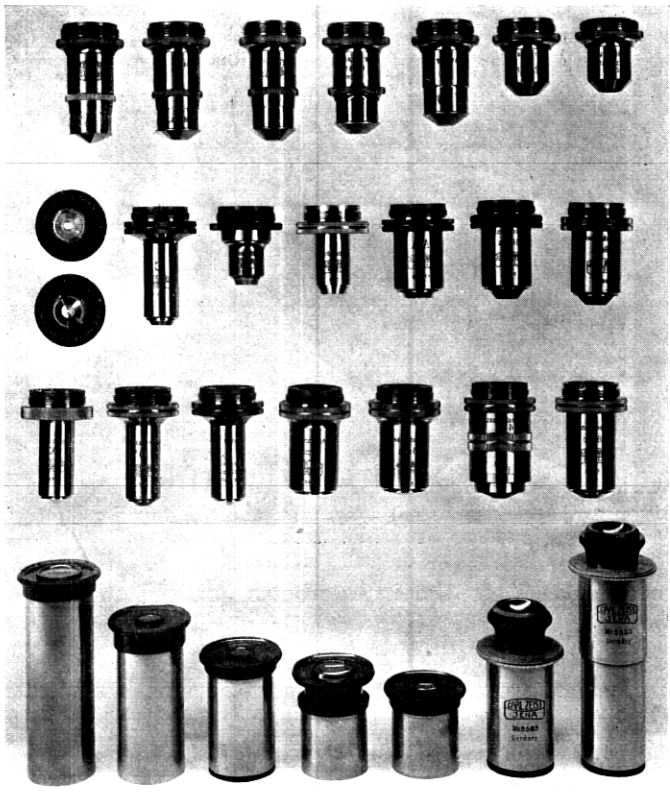


Fig. 5—A battery of medium and high-power objectives and eyepieces.

mersion" series. The term "dry" signifies that the objective when properly used is separated from the specimen by a stratum of air. In the case of the immersion objectives some one fluid for which medium the objective has been computed, such as water, glycerine, cedarwood oil, etc., is used to connect the front lens of the objective with the specimen. The fundamental difference between the dry and the immersion objectives is one of resolution, where by resolution

is meant the ability to see separate and distinct lines as individual units when these lines are spaced very close together. Resolving power or the number of lines per inch resolved is expressed numerically by the equation

$$N = \frac{2\ N.A.}{\lambda},$$

in which N is the number of lines per inch, $N.A.$ is the numerical aperture (defined below) and λ is the wave-length in inches. An objective of high resolving power when correctly used will resolve

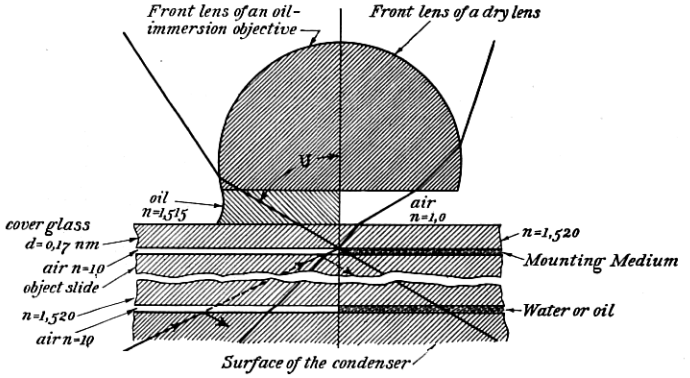


Fig. 6—Diagram illustrating numerical aperture and the superior light gathering powers of an oil immersion objective.

lines spaced 100,000 to the inch, whereas an objective of inferior resolving power under the same condition will not be able to distinguish the lines as distinct units.

As will be seen from Fig. 6, an immersion lens has greater light gathering power than a dry lens of corresponding focal length. This light gathering power is expressed as numerical aperture which term in reality supplies a measure of all of the essential qualities of the objective. The magnitude of the numerical aperture is expressed by the equation

$$N.A. = n \sin U,$$

n being the refractive index of the medium contained between the cover-glass and the front lens of the objective, and U the semi-aperture angle of the system.

For a given magnification and under comparable conditions the resolving power is directly proportional to the numerical aperture. The brightness of the image is proportional to the square of the

numerical aperture. As the numerical aperture increases the depth of penetration (*i.e.*, the power of the objective to resolve detail simultaneously at different depths or distances from the objective), and the flatness of the field both decrease, but usually when high resolution is desired flatness of field and penetration are not of great concern. The value of the numerical aperture varies from about 0.10 in the very low-power achromatic objectives to 1.40 for the oil immersion apochromats.

The eyepieces for use with the achromatic objectives are generally of the Huygens type but those for use with apochromats are termed compensating because of certain corrective measures which they apply to the behavior of this type objective. High-power achromatic objectives and the semi-apochromats may also be used to advantage with the compensating eyepieces. The magnifying power of eyepieces ranges from about 4 times to 20 times although another class termed orthoscopic eyepieces may be procured with a magnifying power of 28. These latter eyepieces are generally used with low-power objectives only. A special type of eyepiece known as a projection eyepiece of low magnifying power is used for certain classes of work when photographing with a long bellows extension. These eyepieces have correction collars which must be set to correspond with the bellows extension used.

Illumination

The color of the light used and the illumination of the specimen play a most important part in photomicrography and the behavior of the finest objective will appear very ordinary unless critical illumination of the specimen is attained. The illuminant is usually some form of arc lamp or metal filament, gas-filled lamp. Both types have their advantages and while many statements may be found derogatory to the use of arc lamps, as a real source of light, the author has found that a smoothly operating automatic arc lamp equipped with suitable carbons is capable of yielding results of the highest order. What is needed especially for medium and high-power work is a point source of light (or approximately so) of great brilliancy; capable of being smoothly and uniformly controlled so that the luminous end of the positive carbon will not fluctuate backward and forward within wide limits. Most automatic arc lamps are designed for a certain direct current value, usually about five amperes and unless the current rating is closely adhered to in practice the operation is apt to be irregular. Sputtering and irregular feeding

of the carbons are due to lack of proper adjustment of apparatus or of current and voltage or to the use of an unsatisfactory grade of carbons. It may be of interest to know that the type of automatic arc lamps used in the Bell System Laboratory are so steady and uniform in their operation that they occasion no concern except for the usual maintenance. Since very small diameter carbons must be used to approximate the point source of light condition, these lamps will operate continuously with one set of carbons for about thirty minutes

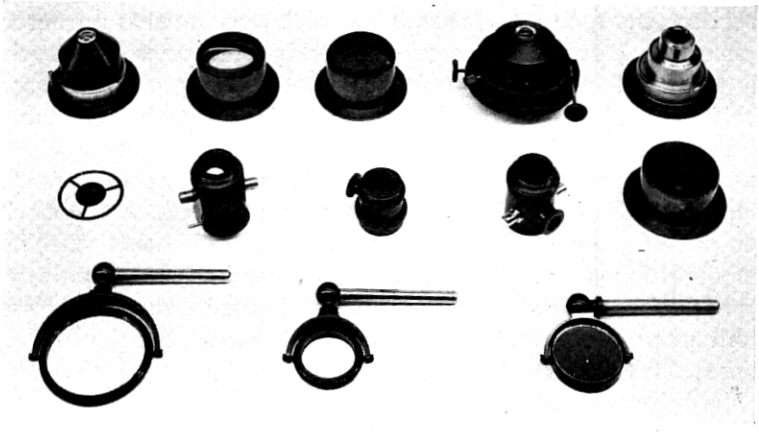


Fig. 7—Condensers and illuminators used in microscopy

only. Frequently exposures are made at high powers (6,000 to 9,000 diameters) lasting from 45 seconds to 3 minutes, during which time the carbons may feed several times and no ill effects result, so perfect is the operation.

Critical illumination is nothing more than bringing the rays of light from the source of illumination to a state of proper focus and optical alignment so that the surface of the specimen under examination will be uniformly and brilliantly illuminated. This matter of securing uniform illumination is by no means the simple operation that the designation implies since usually an optical train consisting of the light source, condenser, diaphragms and an object illuminating device of some sort must all be brought into exact optical alignment with the optical system of the microscope.

For very low-power work or for gross photography of specimens, a gas-filled, metal filament lamp with a suitable condenser and mounted on a portable pedestal which may be adjusted to all angles is very useful. In this case the optical train is dispensed with and the light thrown at the proper angle on the specimen to be photographed.

Great brilliancy is not required for this work but rather a diffused light, obtained by means of interposing a ground glass screen in the illuminating beam.

The object in photomicrography is to record as clearly and as faithfully as possible the structural characteristics of the specimen. This is accomplished by a rendering of contrast between the structural elements of the specimen and by intensifying or diminishing this contrast to suit the particular characteristics which are to be reproduced to best advantage. This control of contrast is obtained by control of the color of the light used for illumination.

A spectroscopic analysis of the light of the arc shows a continuous spectrum consisting of three dominant color portions, blue-violet, green and red which pass by gradation to each other; the blue-violet passes by blue and blue-green to green, and the green by yellow and orange to red.

If an object absorbs some constituent of the white light falling on it then the reflected light will be deficient in this color and as a result the eye will experience the sensation of color.

The effect on the color of the residual light by blocking out a narrow band at different positions in the spectrum is shown in Fig. 7a.

Fig. 8—Diagram representing the spectrum of arc light divided roughly into three dominant bands.

A simple diagrammatic representation of the visible spectrum is shown in Fig. 8, in which the tri-color division is broadly made as follows:

Blue-Violet	4,000 to 5,000 A.U.
Green	5,000 to 6,000 "
Red	6,000 to 7,000 "

An object which appears red to the eye when illuminated by white light is absorbing the blue-violet and the green light, and the bulk of what it reflects or transmits is red. Similarly, an object appears green because it is reflecting or transmitting the green constituents of the spectrum and absorbing the red and the blue-violet rays. These are simple cases assuming sharp absorptions and ideal conditions, but in the practice of the art of photomicrography we are dealing with gradation in color and oftentimes the structural characteristics

of the specimen show little contrast, either within the specimen itself, or between the specimen and the background. Therefore, to reproduce an object faithfully or to accentuate faintly revealed characteristics, careful consideration must be given to the color of the light used when photographing the specimen. For the purpose of separating white light into well defined bands, light filters are used and their function is to filter out rays or bands of rays of certain given wave-lengths. These filters consist of colored gelatine films mounted between flat pieces of glass or of liquids appropriately colored and contained in rectangular vessels of glass with flat and

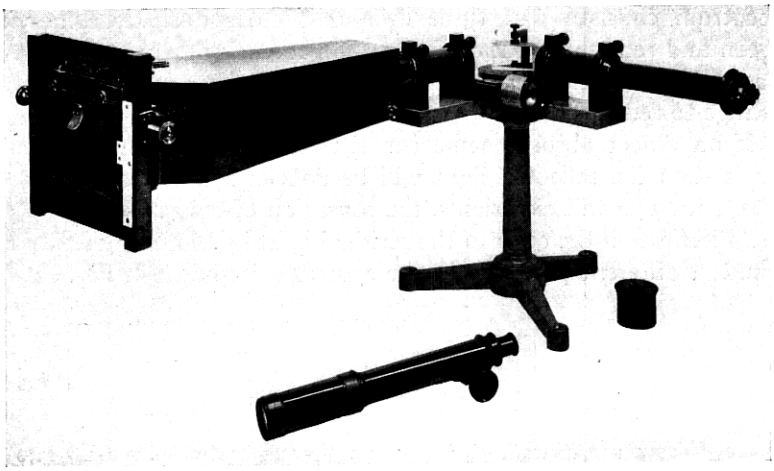


Fig. 9—Hilger wave-length spectrometer. The camera is interchangeably mounted with a reading telescope.

parallel side walls. The "Wratten M" series of gelatine and glass filters is probably the best known and most widely used. The selection of a light filter for a given specimen is usually by experimental methods. Successive filters are inserted in the illuminating beam and the resulting image studied for rendering and definition. However, two simple rules apply generally; if a color is to be rendered as black as possible, then it must be photographed by light of wave-lengths within the absorption band of the specimen; when contrast is desired within the specimen itself, the object should be photographed by light of a wave-length which it transmits. The first rule is of use when it is desired to secure contrast between the object and the background; and the second for better rendering of detail within the object.

Spectrometers are available for determining the characteristics of filters; for determining the transmission spectrum of a micro-

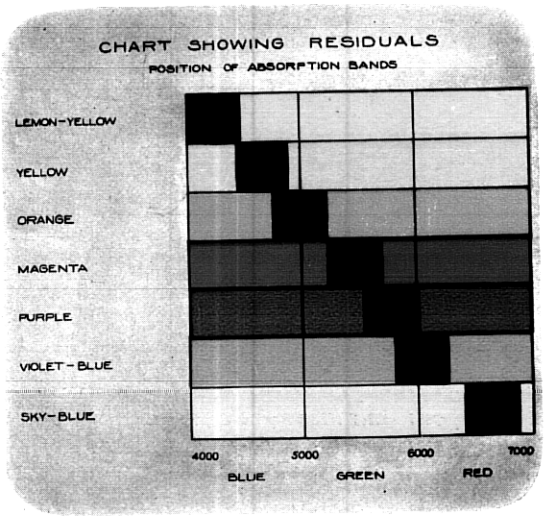


Fig. 7a—The effect on the residual color of arc light by blocking out narrow bands at different positions in the spectrum.

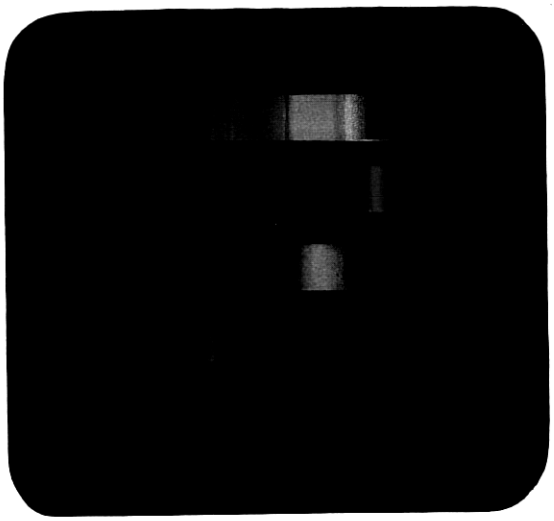


Fig. 10—Direct color photography of the spectrum of arc light and with the Wratten A, B, C and D filters respectively interposed in the beam.

scopic mount; and for studying the effect of dyes or stains on certain types of transparent mounts. For the purpose of filter studies the Hilger wave-length spectrometer constitutes a very useful accessory. This instrument is illustrated in Fig. 9, and in Fig. 10 is shown by direct color photography the residual light from an arc lamp after passing through various filters. The spectrometer is adapted for either direct vision work or photography, a camera and telescope being interchangeable. Instruments for observation with spectroscopically decomposed light constitute what are known as spectroscopic eyepieces and are very useful for certain classes of work, since they replace the usual microscopic eyepiece and may be used with any objective. Precision instruments of this type are capable of measuring the transmission or absorption spectrum of very minute

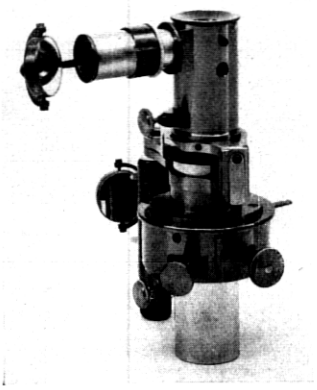


Fig. 11—A spectroscopic eyepiece by Zeiss. This instrument replaces the usual eyepiece of the microscope when it is desired to make observations with spectroscopically decomposed light. It yields an image of the transmission spectrum of the object with a superimposed Angstrom scale and if desired the transmission spectrum of the staining reagent may also be brought into the field of vision. The staining reagents are placed in glass vials.

bodies such for example, as a single blood corpuscle, which state of perfection is said to be attained by the Zeiss instrument, illustrated in Fig. 11.

The wave-length of the light used in photomicrography also has other useful functions to perform and for some classes of work these take precedence. Mention has been made of the correction of objectives for aberrations which are inherent in the simple lens. When an objective, not fully corrected, is used for photomicrography at the higher magnifications, color distortions assert themselves and result in faulty performance of the objective unless filters are used

to exclude light of wave-lengths other than that for which the objective has been computed.

In high-power photomicrography of metallurgical specimens, the purpose, of course, is to attain the maximum of resolution and here the wave-length of the light used plays an important part. As mentioned above the resolving power of an objective may be increased by decreasing the wave-length of the light used. Assuming that a Wratten "F" filter is used whose transmission band is from 6,100 A.U. to the red end of the spectrum, then an objective of 1.4 N.A. should resolve about 109,000 lines per inch. If a "C" filter is used whose spectral transmission is from 4,000 A.U. to 5,100 A.U., the same objective should resolve about 158,000 lines per inch. In other words, by using the shorter wave-length light,[1] it is possible to effect a theoretical improvement of about 45% in the resolution. In practice, these theoretical values are not fully obtained because of other complications entering into the problem.

Polarized Light

Polarized light is oftentimes a very useful aid in the study of transparent objects. By combination with suitable selenite plates color combinations are developed in the specimen and between the specimen and the background which facilitate identification of substances, comparison of known and unknown substances, and the study of their structure. In the field of crystal studies, polarized light is indispensable and it furnishes evidence of a very substantial nature in the field of micro-chemistry. The problem has been presented on occasions to identify the nature of some substance, resulting from the corrosion of some small telephone part. The evidence in these cases could easily be placed on the head of a pin but by the use of polarized light in conjunction with micro-chemical methods, it has been possible to form some sort of a qualitative estimate of the nature of the substance. Polarized light is obtained by means of a nicol prism contained in a suitable mount which is clamped in a ring beneath the sub-stage condenser. The illuminating beam from the microscope mirror is thus polarized before it reaches the condenser. A second nicol prism called the analyser is either contained within a special eyepiece or the analyser takes the form of a mount which may be placed above the usual eyepiece. Both polarizer and analyser are

[1] Regarding the use of ultra-violet light see High-Power Photomicrography of Metallurgical Specimens, F. F. Lucas, Trans. Am. Soc. for Steel Treating; Vol. IV, p. 611, 1923.

mounted so that they may be revolved. Extinction angles are read from a suitably graduated circle usually forming a part of the analyzing eyepiece.

Preparation of Specimens

Specimens, to be investigated or studied by microscopic methods must have a preparatory treatment in all cases except, perhaps, for very low-power work. Many samples require the preparation of transparent sections: that is, a specimen of the object a few thousandths of a millimeter in thickness so that it is transparent or at least translucent; studies of woods, porcelains, papers, fibers, tissues, insulating compounds, etc., are usually made with transparent sections.

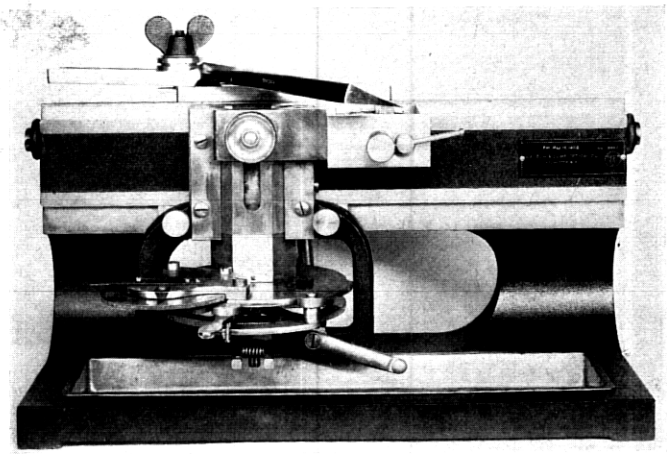


Fig. 12—A sliding microtome for cutting microscopic sections. The work is held in a clamp and a very heavy section razor, flat on one side and hollow ground on the other is operated backward and forward on a slide rails. The return movement of the razor operates the elevating mechanism to which the work is attached so that the latter may be raised to cutting position by predetermined increments.

Hard specimens such as porcelain are prepared by grinding, softer materials such as wood sections are first prepared by suitable softening processes and then are cut in an instrument called a microtome, a form of which is shown in Fig. 12.

Delicate structures require strengthening before they can be cut; these are embedded in paraffin, celloidin or glycerine gum. For successful results gradual and thorough impregnation of the parts is required and this operation may take several weeks. After the

sections are cut, they must be further prepared by being stained, dehydrated and cleared after which they are finally mounted in Canada Balsam or similar mounting medium between a glass microscope slide and a cover glass. Mounts of this kind are permanent, but when it is not desired to retain the mounted specimen for record or future examination, temporary mounts are often made in which the mounting medium is some liquid such as water or glycerine, or

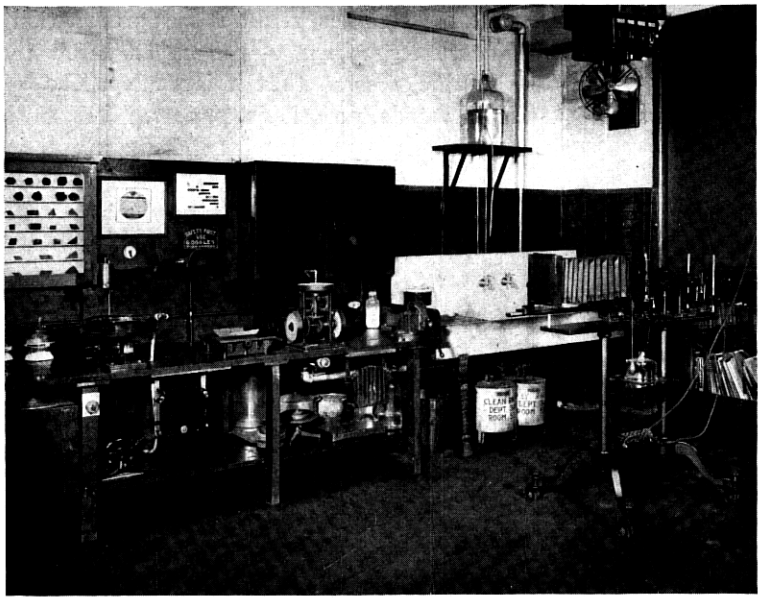


Fig. 14—Equipment for the preparation and preliminary examination of opaque specimens.

in some cases, may be the staining medium itself. An enlarged view of a permanently mounted transverse radial and tangential sections of Douglas Fir wood is illustrated in Fig. 13.

The preparation of metallurgical specimens is accomplished by different methods and if a specimen is to be examined at extremely high powers, the utmost in skill and refinement of methods is necessary. The usual method of procedure is first to file a flat surface on the specimen, after which the surface is gradually brought to a semi-polished condition by rubbing the specimen on a sheet of French emery paper, placed on a plane surface. A coarse grade of paper is first employed and by gradual steps, finer and finer grade papers are used, the rubbing on each successive paper being in a direction at right angles to the preceding paper and continued until the scratches

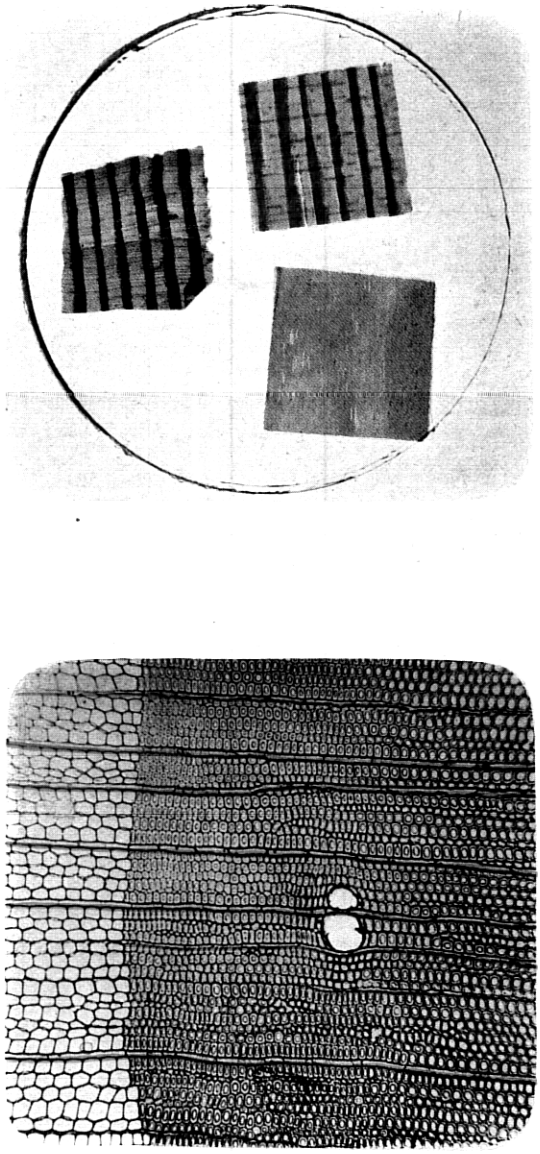


Fig. 13—An enlarged view of a specimen prepared for microscopic examination. The cover glass shown by the circle measures ¾ inch in diameter. The mounts are transverse, radial and tangential sections of a wood specimen and were stained to make their structure visible under the microscope. The appearance of a transverse section of Douglas Fir at 100 diameters is shown in the lower illustration.

of the preceding operation have all been removed and finer ones established in the new direction. This is continued to the 000 paper, after which the specimen is further polished on a polishing machine having a broadcloth covered lap capable of being revolved at varying speeds to about 1,200 rpm. This lap is kept moistened with water and fine alundum is used as the abrasive. This operation gives a

Fig. 15—General view of the Laboratory for Technical Microscopy.

semi-polish and when properly carried out, leaves the specimen with numerous very fine scratches. The final operation is carried out on another lap covered with very fine broadcloth and with an exceedingly fine abrasive such as the finest jeweler's rouge or magnesium oxide. For high-power work magnesium oxide is the only polishing medium which has been found to yield a satisfactory surface. The technique for the development of surfaces at high powers has been worked out in our laboratory so that it is now possible to study metal structures with great clearness at high powers. Equipment for grinding and polishing specimens is shown in Fig. 14.

Metals, after polishing, as a rule, do not show their structural characteristics, but must be treated in some way to etch the polished surface. This etching operation is a simple matter for low-power work, but as the magnification is carried higher and higher, the problem becomes increasingly difficult.

Bell System Photomicrographic Laboratory

A general view of the Laboratory situated on the fifth floor of the building at 463 West Street, New York City, is shown in Fig. 15. Some of the equipment is more fully illustrated in detail views.

It consists of two metallurgical equipments, one of which is the large Zeiss metallographic outfit shown in the foreground of Fig. 15. This equipment is of precision quality and is used for all classes of

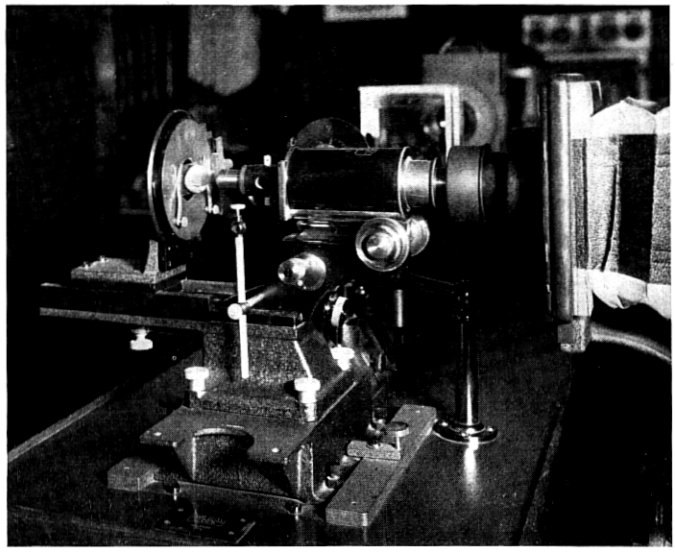


Fig. 16—The Martens stand of the large metallographic outfit. The vertical illuminator is shown between the barrel of the microscope and the objective.

work involving opaque specimens. The optical parts consist of a full complement of Zeiss apochromatic objectives and compensating eyepieces for medium and high-power work. For low-power work a full set of Zeiss micro-planar lenses and a Tessar lens are used. The maximum bellows extension of the camera is 155 centimeters and the plate holders are designed for 24 x 30 centimeter plates and all smaller sizes by employing suitable kits. The illuminating train consists of an automatic arc lamp, a condensing system, and cooling cells, mounted on an optical bench and capable of adjustment to meet the conditions of the work.

Illuminators of conventional types, for vertical and oblique light may be assembled on the Martens type stand. This stand is a departure from the construction of the usual form of microscope stand. It is much more rugged and is arranged for use in a horizontal

position only. In precision work a stand must be stable and substantial and the construction throughout has been arranged with this thought in mind. The microscope is equipped with a movable stage for rough focusing and this is fitted with a revolving mechanical stage so that the specimen while under examination may be moved about at will for the purpose of study or exploration. To facilitate focusing,

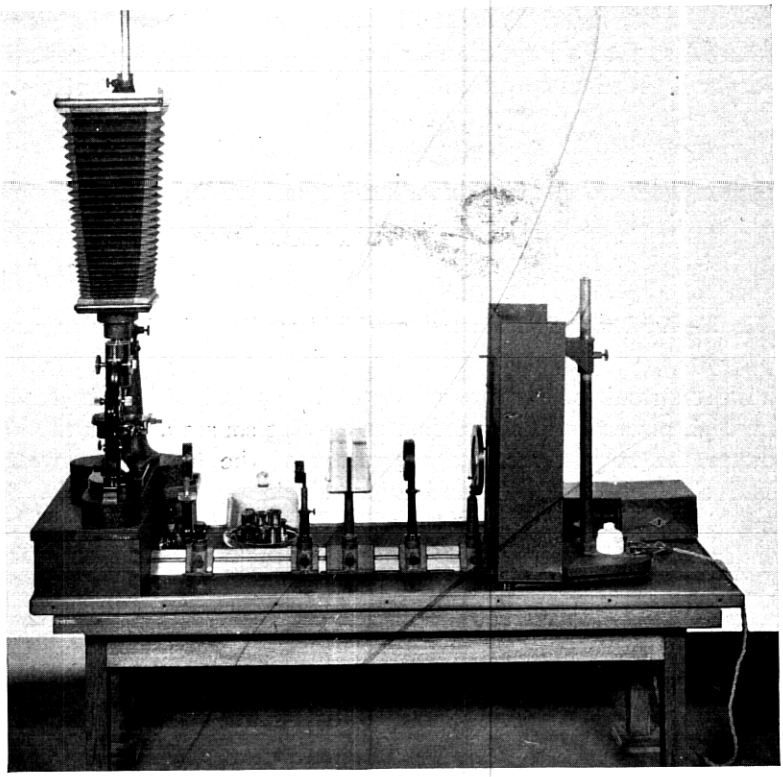


Fig. 17.—A vertical photomicrographic camera for transparent specimens.

gear is provided so that the operator may sit at the ground glass screen and by means of a wooden handle, focus the microscope. A ground glass screen for viewing and for rough focusing and a clear glass screen for fine focusing with a magnifier are provided to be interchangeably mounted with plate holders on the camera back.

A second metallurgical outfit of Bausch and Lomb manufacture shown in Fig. 14, is used for preliminary examination of specimens while in the course of preparation and for photographing some metallurgical specimens at medium powers. This outfit is also arranged

for photomicrography and has a 5 x 7 camera of rather short bellows extension. The objective equipment is of the achromatic type.

For transparent work a Zeiss vertical camera outfit, Fig. 17, equipped with the conventional Zeiss research type microscope is used. The camera has a bellows extension of 80 centimeters and uses 5 x 7 or smaller plates. It is fitted with ground and clear glass focusing screens similar to the large Zeiss metallurgical outfit. The illuminant is a 500 watt metal filament nitrogen filled bulb with the filament mounted so that a large circular area of illumination is presented, or if desired, the filament assembly may be turned sideways and a single

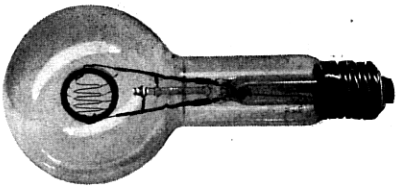


Fig. 18—A 500 watt metal filament, gas-filled lamp for use in photomicrography.

filament strand is thus presented to the optical train. In medium and high powers, this approximates a point source and for the lower powers the large circular arrangement of the filament provides a relatively large area of illumination which is quite desirable. The lamp is illustrated in Fig. 18. The illuminating train consists of condensing and cooling units adjustably mounted on a substantial optical bench as in the case of the metallographic outfit. The objectives consist of a full set of apochromats and also several achromats of low power. The micro-planars are also used with this equipment.

The Ultra-Microscope

The ultra-microscope is an instrument for revealing the presence of very minute bodies present as colloids in transparent solids or liquids. The presence of these particles is made apparent by the light rays which they intercept and diffract upward into the microscope objective. It is a matter of common observation that dust particles are seen in an intense beam of light such as sunlight but otherwise their presence remains concealed. This principle of illumination is made use of in the ultra-microscope as described below and accordingly differs considerably from the conventional arrangement of compound microscope and illuminant.

The appearance of ultra-microscopic particles in fluids and transparent solids as seen by means of the ultra-microscope is, without a

doubt, one of the most fascinating and spectacular demonstrations within the scope of technical microscopy. A beaker containing water with a drop or two of glue or soap, or containing benzol with a few drops of a rubber solution stirred into it, or even some rather dirty looking oil which has seen service in some machine, do not constitute

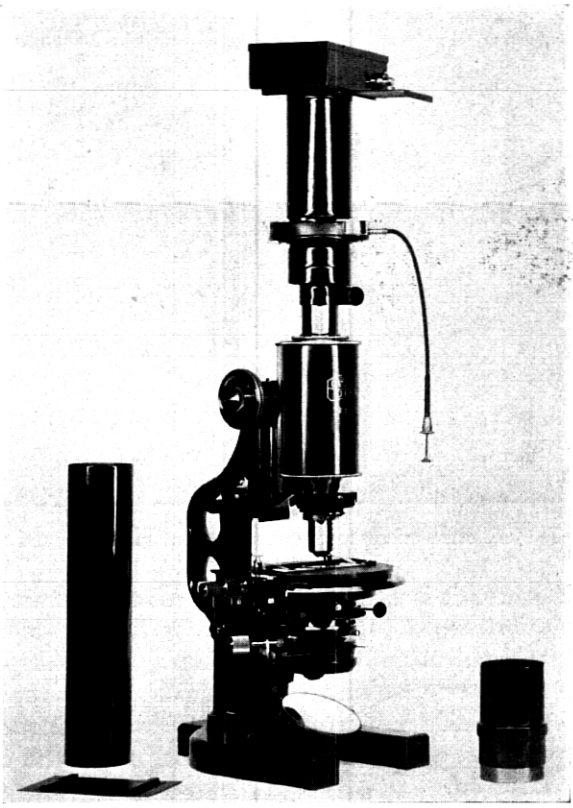


Fig. 19—A small photomicrographic camera developed by the writer and used extensively in the laboratory for photographing on film, or on plates. It is used when a large number of small specimens are to be reproduced or when a large field is unnecessary.

interesting exhibits as viewed in the beakers, but placed in suitable cells for ultra-microscopic examination, these liquids come to life and display the colloidal particles coming into vision as tiny illuminated particles, only to burst into rings of light and pass away into the dark background. The constant irregular motion is the Brownian movement and the smaller the particle the more lively it moves. Conglom-

erate masses of particles merely float through the field of vision and, compared with the individual particles, appear exceedingly sluggish.

Fig. 20 gives a general view of the Zeiss ultra-microscope as originally devised by Siedentopf and Zsigmondy. The equipment has been superseded to some extent by the later Siedentopf cardioid ultra-microscope. The latter is a very powerful light-concentrating device

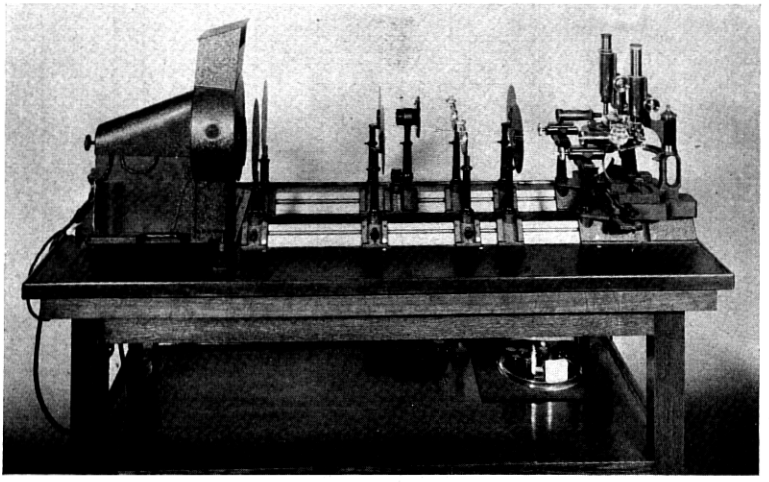


Fig. 20—The Slit ultra-microscope for transparent solid or liquid specimens.

and for this reason it is primarily adapted for the examination of fine colloidal solutions and dilute precipitates as well as for the observation of micro-chemical and photo reactions. For transparent solids and for the precursory examination of liquids and for rapidly passing in review several fluids in succession, the original arrangement retains marked advantages. The cardioid ultra-microscope will be described more fully later on.

Fig. 21 shows diagrammatically the path of the rays within the preparation in the presence of ultra-microscopic particles and will serve to make clearer what is to follow. In the original form of ultra-microscope (Fig. 20) the horizontal incident rays which go to furnish the illumination do not enter the microscope, the latter being set up vertically and hence the background appears dark. The only rays to enter the objective of the viewing microscope are the diffracted rays which come within the aperture of the objective.

At one end of the base board is an automatic arc lamp mounted on slide rails so that it may be brought in line with either of two illuminating trains mounted on optical benches.

One of these illuminating trains functions with a microscope which has mounted on its objective a clamping device for holding Biltz cells in which the liquids are placed for examination. The other train serves another microscope on the stage of which is mounted a special object stage capable of being raised and lowered and provided

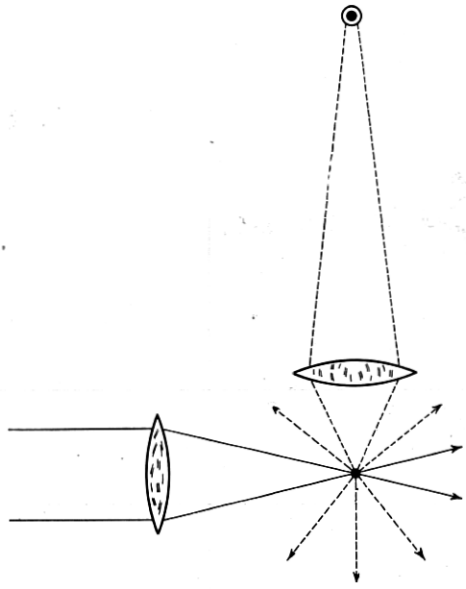


Fig. 21—Illustrating diffraction of light impinging upon an ultra-microscopic particle. Illuminating rays represented by solid lines and diffracted rays by dotted lines.

with a plate at the top to receive the specimen to be examined. In this case the specimen, if a hard solid, has been previously prepared to have two ground and polished surfaces in planes at right angles to each other and is mounted so that one faces the illuminating train and the other the objective of the viewing microscope. Plastic substances or certain liquids not suited to the use of the Biltz cells are placed in a special glass cell having a deep cylindrical recess faced with a quartz window toward the illuminating train. Various cells for ultra-microscopic examinations are shown in Fig. 22.

Placed next to the arc lamp is a fixed diaphragm and then a small projection lens which is corrected chromatically and spherically and brings the image of the positive carbon of the arc lamp to a focus on the adjustable slit. The slit is provided with a drum bearing a scale. The divisions of the scale embrace 50 parts and a complete revolution of the drum opens the slit ½ mm. so that each division of the scale advances the slit 1/100 mm. The slit is fitted with two jaws at right

angles to the principal slit, one being adjustable by a milled screw head. The function of these jaws is to limit the length of the slit. The slit head may be given a quarter turn so that it may be set horizontally or vertically, which is necessary in order to calibrate the instrument as explained later. A projection lens next in order toward the microscope projects the image of the slit into the image plane of a horizontally mounted objective which is mounted on a stand with cross

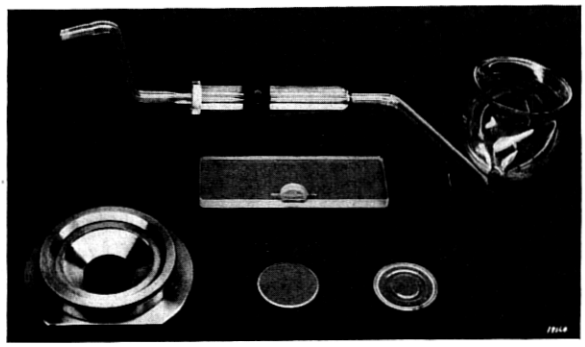


Fig. 22—Cells used for the examination of fluids with the ultra-microscope.

slides so that the objective which serves as an illuminator may be moved horizontally in two directions, at right angles to each other. The movement of the cross slides is controlled by screw adjustment but for coarse adjustment in the direction of the illuminating train a sliding sleeve adjustment is made. By this means the illuminating objective can be centered with respect to the observing microscope objective. In the correct position the front lens of the illuminating objective is about 1 mm. from the mount of the observing objective.

The Biltz cell has a rectangular cross section which permits of accurately adjusting the cell in position. A thistle funnel at one end is for the reception of the liquids; the other end is provided with a piece of rubber tubing which has a pinchcock to prevent the escape of the fluid. The rectangular section of the cell has two quartz windows, one of which normally faces the illuminating objective and the other the observing objective. The cell is attached to the observing objective by means of the clamp mentioned and the cell is focused in the proper position in the beam of light by racking the microscope draw-tube upward or downward in the usual manner by the coarse and fine adjustments. The observing objective is a special water immersion objective which makes contact with the upper window of the Biltz cell through the medium of a drop of distilled water.

Quantitative investigations are made by counting the visible particles in a given volume of the fluid and the manner in which so novel an investigation can be accomplished by optical means should prove of general interest. One method consists in the use of the eyepiece micrometer which is substituted for the ordinary eyepiece of the observing microscope. The eyepiece micrometer is ruled into squares and the dimensions of these are found by calibration with a stage micrometer. The depth of the stratum is measured by turning the slit head through a right angle and thus a solid is blocked out in the path of the light rays, whose length and breadth are defined by the rectangular area of the micrometer eyepiece and whose depth is

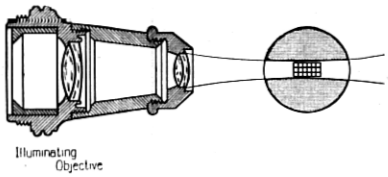


Fig. 23—Illustrating the adaptation of micrometry to the ultra-microscope for the purpose of counting particles per unit volume.

that of the light beam and may be read from the known dimensions of the eyepiece micrometer. Fig. 23 shows the cross ruling of the eyepiece and the pencil of light which traverses the field. The length of the side of each square as seen through the water immersion objective with a tube length of 160 mm. has an approximate value of 9 μ as referred to the object, which value is sufficiently accurate for ordinary measurements. Where more exact measurements are required, the ruling is calibrated for the eyepiece and objective by means of a stage micrometer in the manner to be described under the subject of micrometry.

For studying the behavior of particles in polarized light the eyepiece is fitted with an analyser. In a measure, as the particles decrease in size they become more strongly polarized in degree towards the plane which passes through the axis of the illuminating and diffracted rays, i.e., the principal plane of diffraction. The analyser also serves to distinguish unpolarized from polarized light.

The apparatus for examination of solids is identical in so far as the illuminating train is concerned with the apparatus for liquids just described. It differs only in the character of the specimen or of the cell used and, while designed primarily for transparent solids, it may be used with a suitable cell for liquids also. When liquids are being examined, there is no need for searching the specimen since

the particles are in constant motion, but when solids or semi-solids are being examined it may be desirable to do so. The mechanical stage of the microscope on which is mounted the adjustable specimen stage allows any layer in the specimen to be brought into accurate focus and hence various strata of the specimen can be examined one

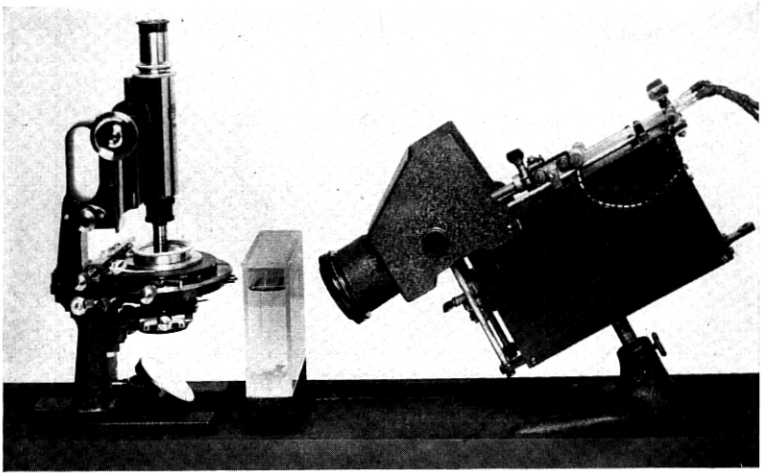


Fig. 24—Cardioid ultra-microscope.

after the other. As previously stated, the specimen must be provided with two polished surfaces at right angles to each other to correspond to the quartz windows of the Biltz cell.

Since the observation of ultra-microscopic particles in polarized light supplies useful information respecting their form and color, a polarizer is provided with a hinged stand so that it may be swung out of the optical train. The analyser, as previously mentioned, is fitted over the eyepiece of the microscope.

The cardioid ultra-microscope illustrated in Fig. 24 differs only in two important features from the ordinary form of microscope. The illumination of the fluid under examination is obtained by a dark-ground condenser mounted in the sub-stage condenser collar and to which Zeiss has given the distinctive name "cardioid condenser." A diagram of the condenser and the paths taken by the rays is illustrated in Fig. 25. Since the aperture of the rays brought to a focus by the condenser exceeds 1.0, it follows that no light can emerge from the condenser if there be a stratum of air above the condenser. It is therefore necessary to connect the object slide

or cell chamber and the top of the condenser by a stratum of immersion fluid free from air bubbles. Cedar oil or pure water is used for this purpose. The chamber for the cardioid condenser is illustrated in Fig. 22. The chamber is made of quartz glass and consists of a circular disc having on one side a circular groove and an optically plain central portion within the groove about 2 μ below the plane outside the groove. A drop of the fluid to be examined is placed on this depressed central portion and a cover glass of quartz placed over it. The excess fluid is expelled to the annular groove and a stratum about 2 μ in thickness is retained in the central portion of the chamber for microscopic examination. The cell is assembled in the metal mount which has a clamping ring and a recessed member

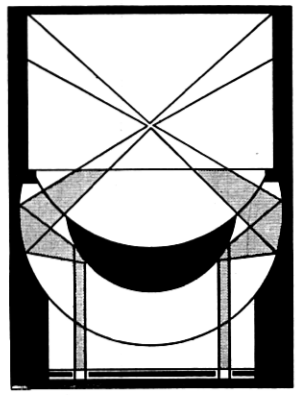


Fig. 25—Diagram of the rays in a cardioid condenser.

to receive it. The very brilliant illumination resulting from the cardioid condenser would cause glass to fluoresce and for this reason a quartz cell is used. Moreover, glass is more liable to be affected by corroding agents than is quartz.

The utmost care must be taken to prepare the cell chamber. This includes washing with alcohol and water; dipping in boiling sulphuric and chromic acid solution; washing in tap water; rinsing in distilled water and then in redistilled alcohol; drying in a hot air current and finally cooling under a bell jar; all of which is necessary to insure absolute cleanliness.

An automatic arc lamp is used as a source of illumination and the image of the crater is projected by a projection lens onto the mirror of the microscope from which the rays are reflected upward into the cardioid condenser.

The objective used with the cardioid condenser is a special apochromat 3 mm. 0.85 N.A. glycerine immersion lens which constitutes a homogeneous immersion lens for cover glasses of fused quartz. This type of objective is necessary because the success of the observation is then largely independent of impurities and slight blemishes on the upper surface of the cover glass, moreover, the lens confers a greater immunity from the effects of varying cover-glass thickness and the immersion fluid precludes the entrance of dust which would gradually cloud the image.

Slit ultra-microscopes are not arranged for photography because in the case of liquids the particles are in a rapid state of motion and the illumination is insufficient. Since in transparent solids the particles are stationary, the image seen in the slit ultra-microscope may be reproduced by making a lengthy exposure. With a small photomicrographic camera developed by the writer the image seen in the slit ultra-microscope for solids has been reproduced and, by instantaneous photography, the moving particles in liquids as seen in the cardioid instrument. Except for purposes of evidence or record, there is little to be gained by photographing with the ultra-microscope.

Dark-Ground Illumination

The dark-ground illuminator constitutes another aid to microscopic investigation. This, in reality, is a sort of ultra-microscope, since the objects are viewed by diffracted light much in the same way as in the cardioid type of equipment. This method of illumination is accomplished by stopping out the axial rays and allowing those of greater aperture to strike the specimen at an angle. The usual form of condenser may be made to yield dark-ground illumination by the simple expedient of inserting a central stop in the path of the light rays just below the sub-stage condenser in a ring provided for such purpose. Better results are attained by use of dark-ground illuminators which are special condensers designed with this object in mind. Dark-ground illumination furnishes valuable means for bringing into view objects which are smaller than about 1 μ. Examples of such objects are furnished by fibers, fine crystalline needles, fissures, edges, rods, bacteria, etc. Under dark-ground illumination methods, these objects are easily seen and studied, whereas with transmitted light, they can be seen with difficulty unless rendered distinguishable by staining. Certain bodies with laminar markings are also suitable subjects for dark-ground studies and in this case the markings are distinguishable more by reason of dissimilarities in refraction than by differences in coloring.

Micrometry

Micrometry plays an important part in technical microscopy because the dimensions of micro-constituents in a specimen are helpful for purposes of identification or for forecasting physical properties. In metallography the measurement of grain size is assuming importance for certain alloys and in some cases, specifications are so drafted as to define this characteristic.

For measuring objects under the microscope, the eyepiece contains a glass disc on which fine divisions have been ruled. In some cases, these rulings take the form of a cross-section composed of small squares or rectangles. The reading of each division of the eyepiece micrometer is calibrated for each objective by comparison with a standardized stage micrometer. These stage micrometers are glass microscope slides on which known units of length have been accurately ruled, such as 1 mm. divided into one hundred parts or 3 mm. divided into tenths and one-tenth divided in hundredths of a mm., etc. The stage micrometer is focused in the same way as a microscopic specimen and adjusted into position so that the rulings of the eyepiece micrometer are superimposed on them. It is then possible to evaluate the eyepiece rulings in terms of the standardized stage micrometer, after which the latter is removed and the specimen to be examined substituted in its place. Thereafter, the image of the eyepiece rulings will be superimposed on the image of the specimen and measurement can proceed. For precision work, a very accurately made eyepiece micrometer is used, a typical form of which has a thin glass plate upon which is ruled a cross and a double line. This is mounted on a slide immediately below a stationary micrometer scale and can be moved by means of micrometer screw. The cross is accurately set by the micrometer screw to coincide with the particle to be measured, the double line serves to count complete revolutions of the screw with the aid of the scale which is seen in the field of vision. The screw carries a drum which has 50 divisions and each division corresponds to a displacement of the cross through a distance of 0.01 mm. so that a complete revolution of the drum displaces the cross 0.50 mm. The actual readings of each interval of the drum head must be accurately calibrated for each objective by means of a stage micrometer. A group of instruments for use in micrometry is illustrated in Fig. 26.

Applications of Photomicrography

In closing, attention is directed to the photomicrographs comprising the Appendix of this paper, each of which was taken in connection with

some definite engineering problem involving telephone apparatus. As the useful range of microscopic vision is extended farther and farther into the realm of higher magnifications, a more exact knowledge of materials is obtained and the effect is learned of physical and chemical forces acting to destroy or to build.

It has been conceded quite generally that about 1,500 diameters of magnification represents the limit of useful magnification. As previously stated this is a much disputed question. Laboratory studies, painstakingly carried out over a period of several years, have

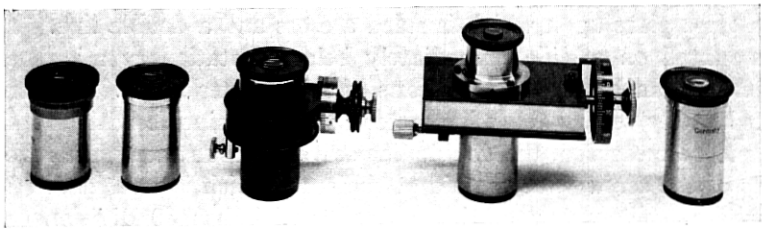


Fig. 26—Various types of eyepiece and stage micrometers used in connection with the microscope to obtain the dimensions of microscopic objects.

accomplished improvements in technique and in precision of adjustment of the equipment which have shown that remarkable resolution, depth of penetration and clearness can be attained in the case of metallurgical specimens, at extremely high powers. There seems little reason to doubt that our knowledge of metals can be augmented very materially by studies of their structures at high powers.

Moreover, it seems probable that the finest high-power objectives are of a quality beyond our ability to use them to best advantage because of our incomplete knowledge of how best to prepare specimens for examination at high powers.

It is impressive to evaluate magnification in terms more readily comprehended. For instance, the cross section of the average metallurgical specimen may be considered as a square whose side measures one-half inch. If we magnify this specimen 100 times, obviously we have an area measuring 50 inches on the side, but if we magnify it 10,000 times, then we have the equivalent of an area about 415 feet on a side or roughly, about four acres. An average picture at 6,000 diameters is 6 inches in diameter and therefore by a reverse order of reasoning, the actual area of the specimen under observation becomes 1/1000 inch in diameter.

APPENDIX

Fig. A. Meteoric iron consists of iron, nickel and the other elements usually found in steels such as carbon, sulphur, phosphorus, etc. The study of meteorites has contributed much valuable knowledge to the science of metallography. The Widmanstätten figures (shown by the arrangement of the constituents with reference to crystallographic planes) were generally considered characteristic of meteoric iron and it was believed that they were not to be found in manufactured iron and steel. Later this was shown to be an incorrect view.

(a) A meteorite which fell at Carthage, Tenn., containing 89.46% iron and 7.72% nickel and which shows the octahedral Widmanstätten structure. Magnification 4 X.

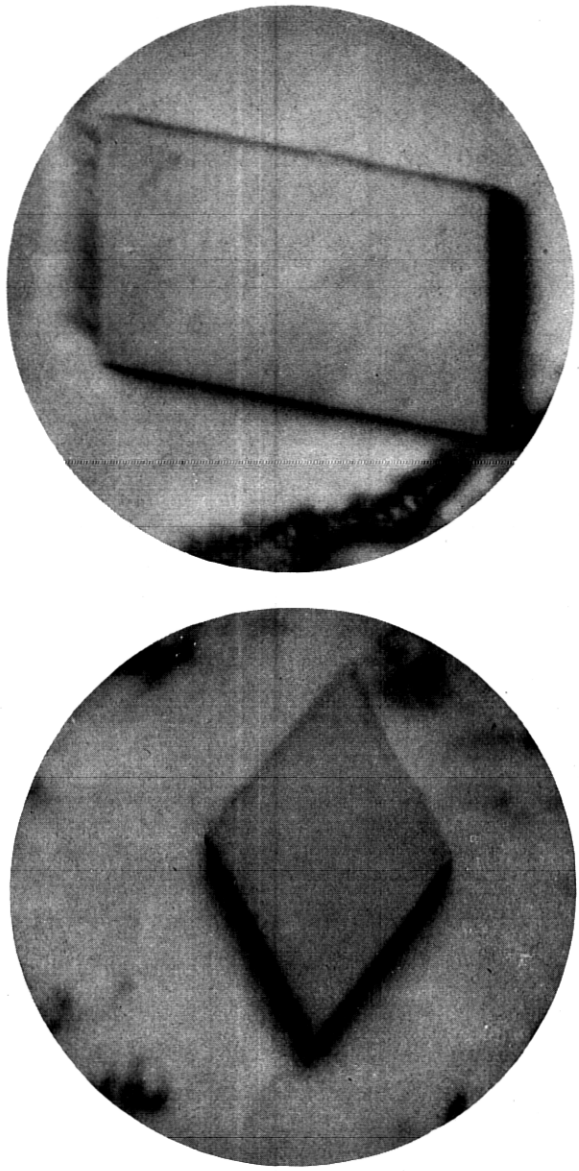


Fig. A

(b) Meteoric Crystals. The figures are sections through an octahedron and were developed by suitably etching a polished surface of the meteorite. Their perfect form is indicative of very favorable conditions of growth and is a corroboration of the octahedral crystalline form of the meteorite. Magnification 3500 X.

Fig. A

(c) A cast steel of 0.5% carbon in which the Widmanstätten or cleavage structure has developed somewhat similarly to that shown in the meteorite. The physical characteristics of the steel are dependent on the structural arrangement of its constituents, in this case pearlite (dark) and free ferrite (light). By suitable heat treatment this coarse structure may be refined and the physical properties of the steel greatly improved. Magnification 100 X.

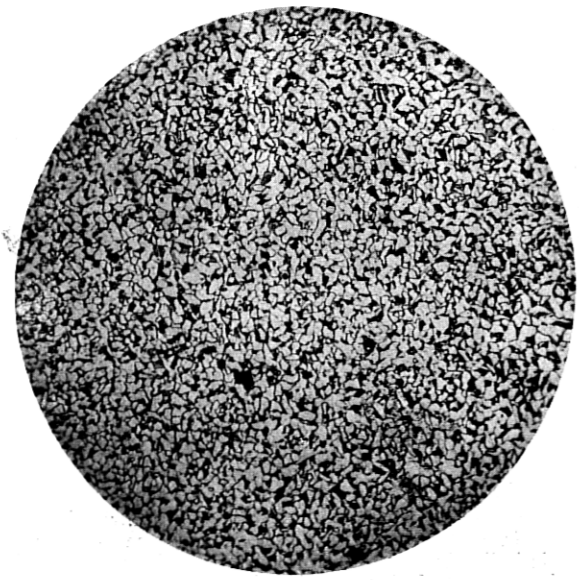


Fig. A

(d) The same steel as illustrated in "C" but after being refined (heated to 1000°C; air cooled; reheated to 650°C, and again air cooled.) Magnification 100 X.

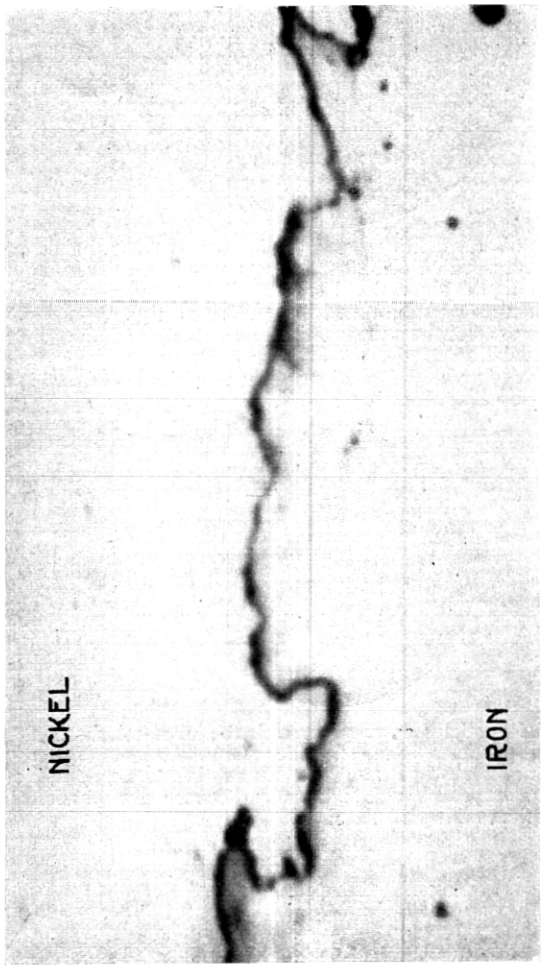


Fig. B. The application of high-power photography to the study of nickel finishes. One of the characteristics of an improved process for plating ductile nickel on iron is the interlocking or "keying" of the nickel and the iron Magnification, 6000 X.

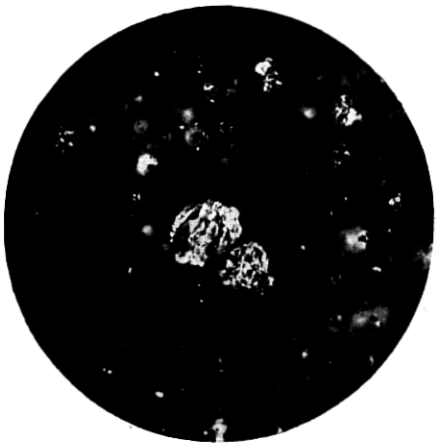
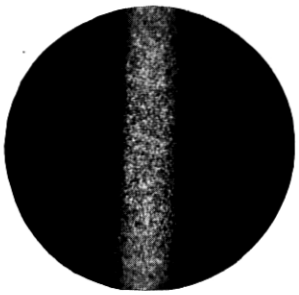


Fig. C. Distribution of filler particles in soft rubber insulation as revealed by a transparent section. The section was cut in a microtome by "flashing" the rubber with liquid air which hardened it just sufficiently to cut properly. The specimen was photographed by polarized light and with selenite plates to secure contrast between the particles and the embedding rubber compound. Note agglomeration of the particles into large masses. The ideal condition of distribution would be attained when each individual particle is surrounded by rubber. Magnification 720 X.

Fig. D. Colloidal particles as seen through the ultra-microscope.

(a) Polymerized particles in a phenolic resin solution. Taken with the cardioid ultra-microscope and the Lucas Photomicrographic camera. Instantaneous exposure was necessary because the particles were in constant motion. Magnification, 220 X.



(b) Coloring matter in glass. The glass was colored saffranin and was transparent to the eye or with any other method of microscopic vision but with the slit ultra-microscope the colloidal coloring matter becomes visible. Also taken with the Lucas photomicrographic camera, a time exposure being necessary. Magnification, 100 X.

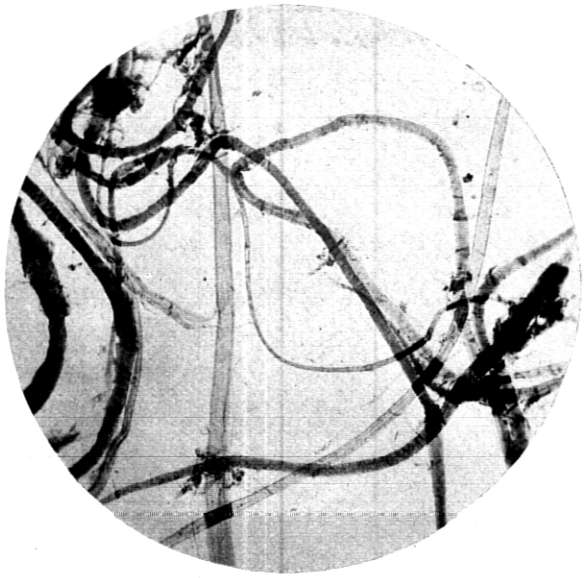


Fig. E. Paper fibers by 97 X. Note the surface markings: the gradation in color and the appearance of roundness possessed by some of the fibers. The photograph was taken with a modern medium-power apochromatic objective.

Microscopic examination of textile and paper fibers affords a means of identification second to none. The fibers are recognized by characteristics peculiar to each and by color reactions to different stains. Cotton, for example, appears as a flat ribbon-like fiber twisted spirally; linen is round and shows "joints" and cross markings. The specimen illustrated consisted mostly of linen with a small proportion of cotton added.

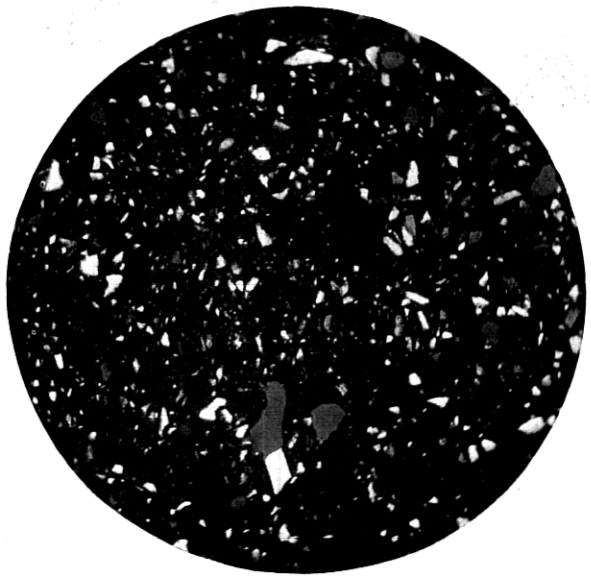


Fig. F. Electrical porcelain by polarized light, magnification 100 X.

The quality of the porcelain may be judged to a considerable degree by a microscopic examination. The degree of vitrification is indicated by the rounding of the sharp corners on the quartz grains; whether or not the porcelain is homogeneous may be determined by the uniformity in distribution of the undissolved particles, and fissures, cracks, or voids are readily seen. All of these factors influence the physical characteristics of the porcelain.

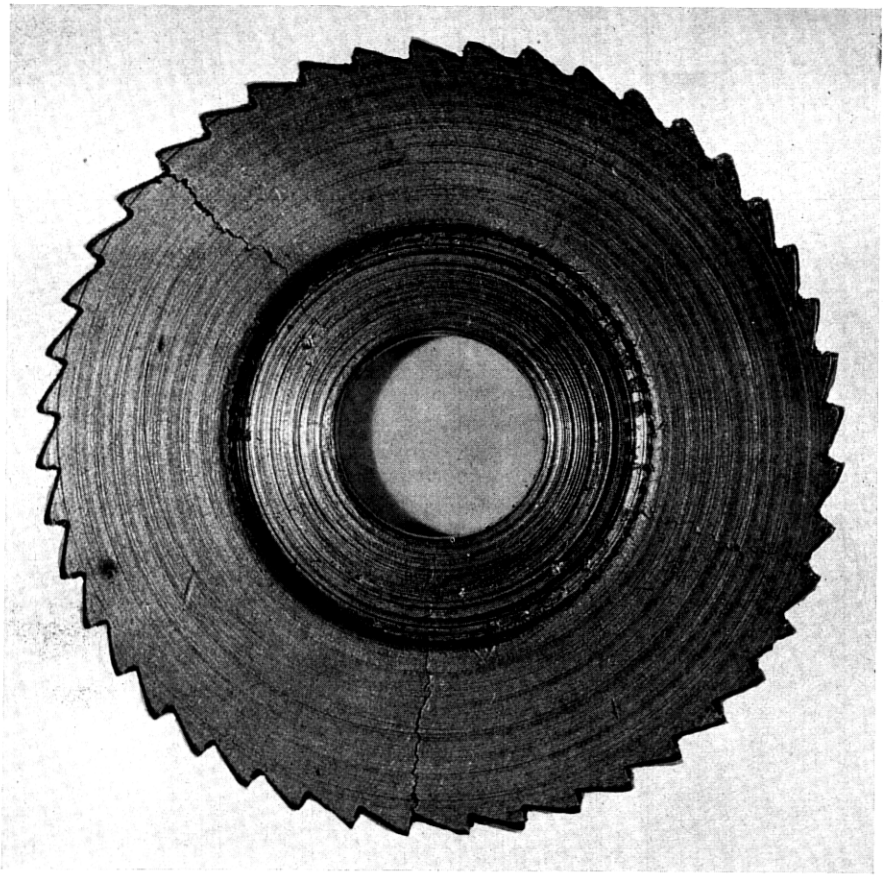


Fig. G. Season cracking of aluminum bronze ratchet wheels.
(a) Ratchet wheel at magnification 2¾ X.

Fig. G

(b) Showing a large crack, at magnification of 23 X.

Fig. G

(c) Intercrystalline nature of the cracks and the severely worked condition of the metal as indicated by several groups of slip bands traversing each crystal grain.

These ratchet wheels developed radial cracks while in storage or in service. Some of the cracks were so large as to be plainly visible to the unaided eye and others were of microscopic dimensions. They resulted from the metal being severely cold-worked at the time the parts were machined and then left in a strained condition. The intercrystalline nature of the cracking is shown in "c" which is characteristic of season cracking. This illustration also shows the crystal grains traversed by several groups of slip bands, indicating the severity of the cold-working.

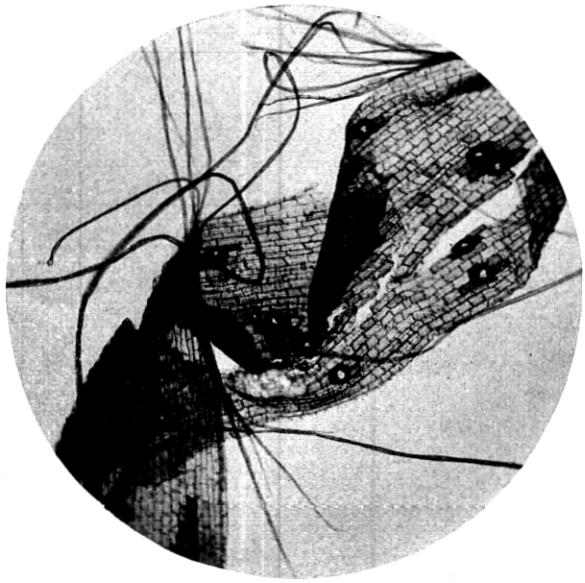
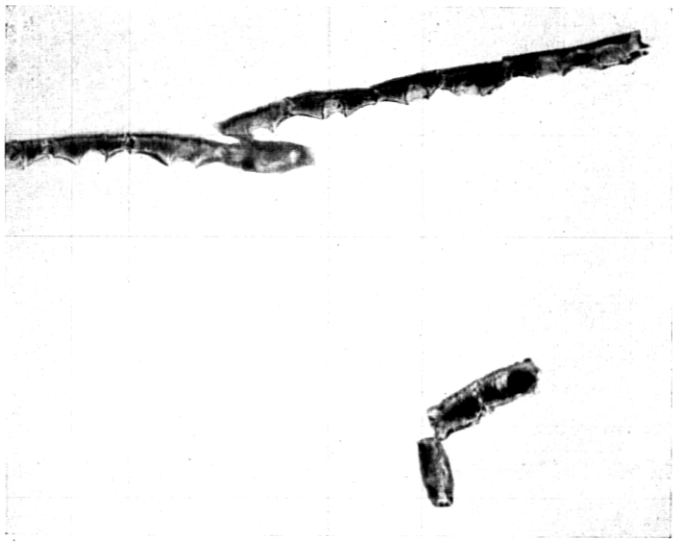


Fig. H. Manila hemp rope is used extensively in telephone work and the fiber from old rope is used in paper for cable insulation which finds its way into the plant.

Microscopically the fiber is identified by certain characteristics, prominent among which are the silicified tabular cells known as stegmata. If the fiber is burned and treated with dilute acid the stegmata remain behind, resembling strings of beads.

Manila hemp makes the best cordage but it is somewhat difficult to distinguish the fiber from that of sisal which produces inferior cordage. The presence of the silicious skeletons of the stegmata and the color of the ash (grayish-black in the case of Manila hemp and white in the case of sisal) aid in the identification of the fiber.

(a) Manila Hemp Fibers, magnification 50 X.



(b) Ash of Manila Hemp, magnification 450 X.

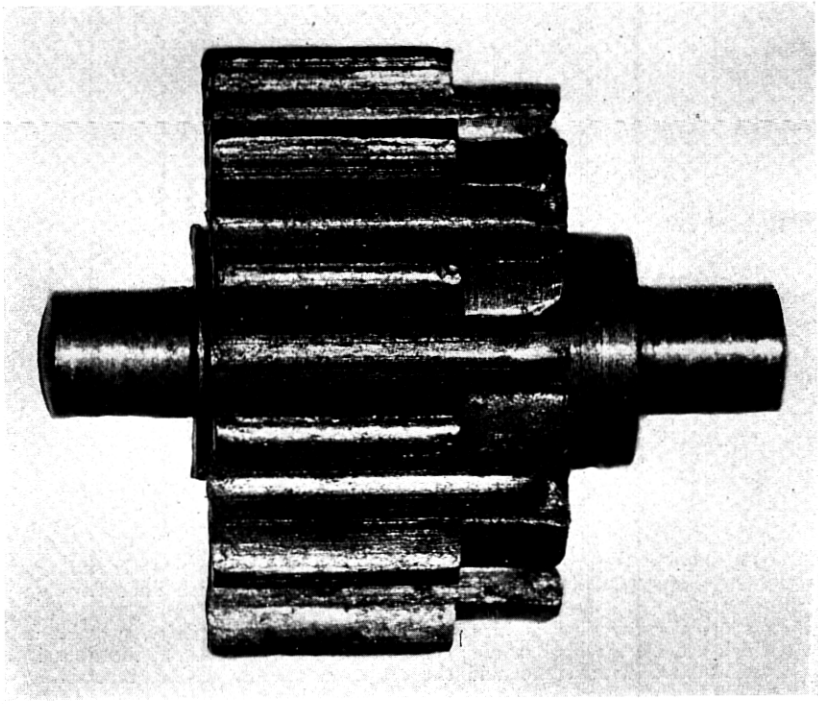
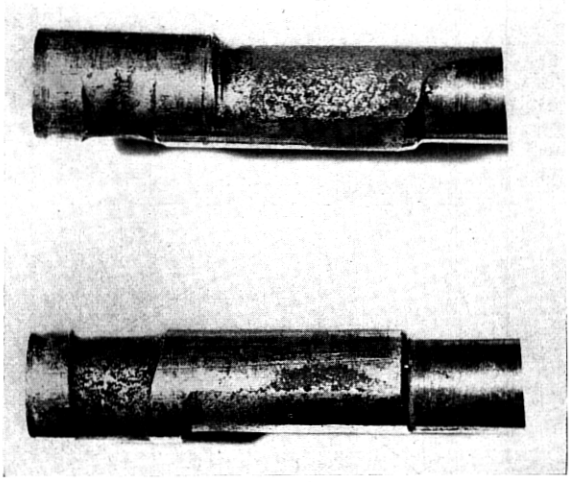


Fig. I. A further illustration of low-power photomicrography in the study of telephone parts:
(a) Intermediate pinion of calling dial. Diameter of pivot .050 inch. Magnification, 14 X.



(b) The effect of laboratory wear tests on small shafts. Magnification, 4 X.

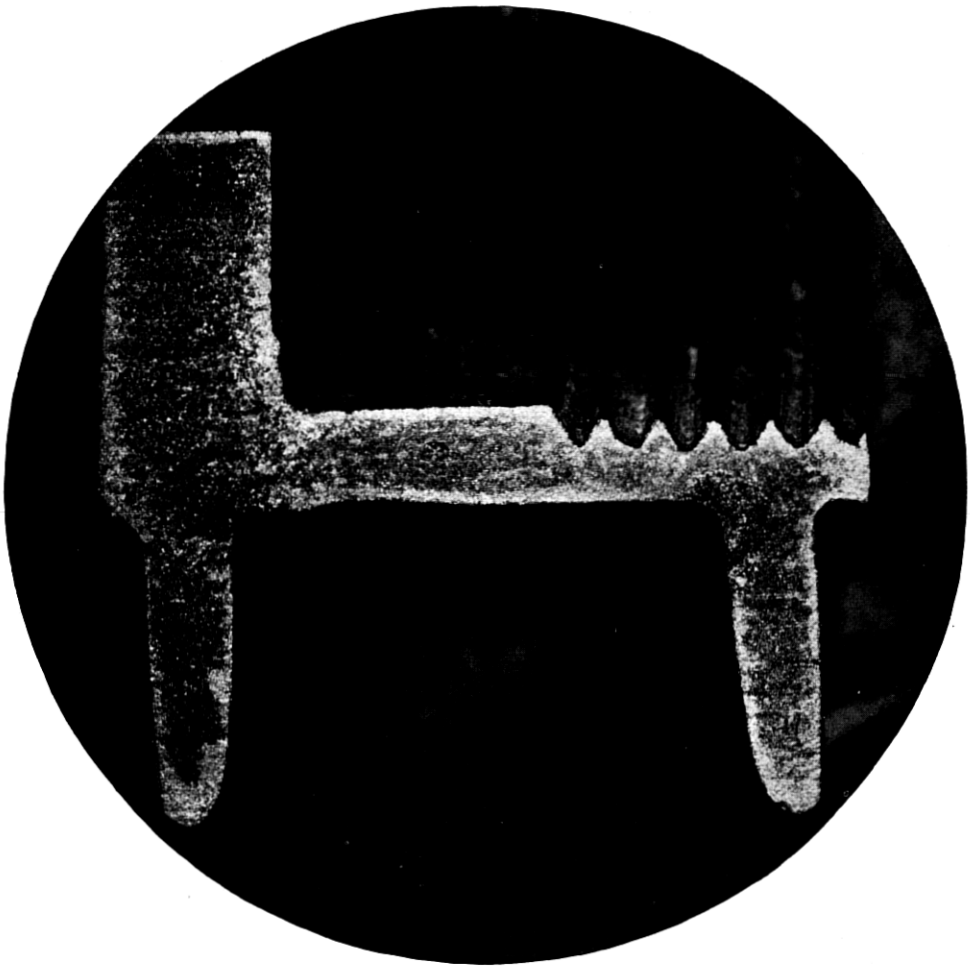


Fig. J. (a) Faulty pack hardening of car wheels for toll ticket distributing system. The object of pack hardening is to impart a highly carburized wearing surface to the otherwise soft steel part. The interior remains soft and ductile. Lack of uniformity in hardening or insufficient depth of the carburized zone causes soft spots which result in unequal wear. The magnification is 11.2 X.

Fig. J

(b) Showing inappreciable depth of carburized zone, and a large non-metallic inclusion in the steel. Inclusions of this sort denote poor quality or dirty steel. Magnification, 100 X.

Fig. K. Steel of 1.5% carbon heated to 825° C. and quenched in oil. This medium-power photomicrograph at 100 X really tells very little about the steel, except that it possesses a fine structure.

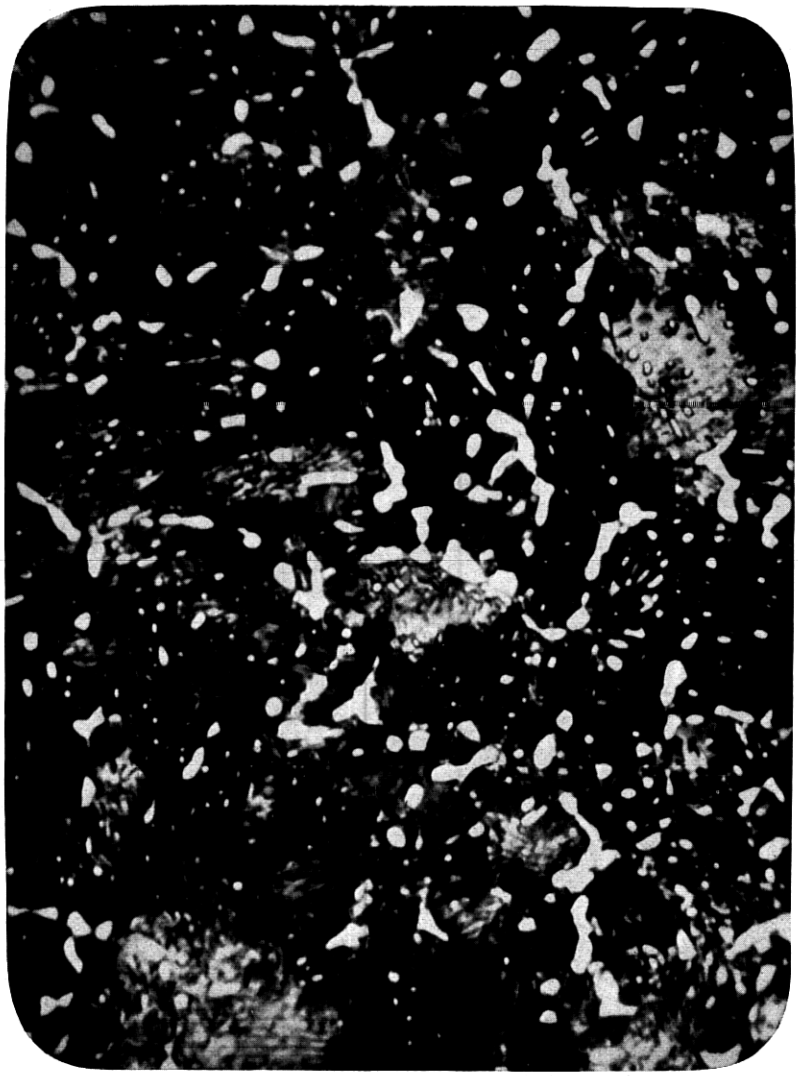


Fig. K. (*continued.*) At 2170 X the specimen is seen in the process of being converted to spheroidized cementite. The cementite (iron-carbide) which is the light constituent is in the process of transforming from a laminated form to small globules. Grain boundaries are still marked by accumulations of cementite but this is spheroidizing. In the light patches stratification of Ferrite and cementite is just visible.

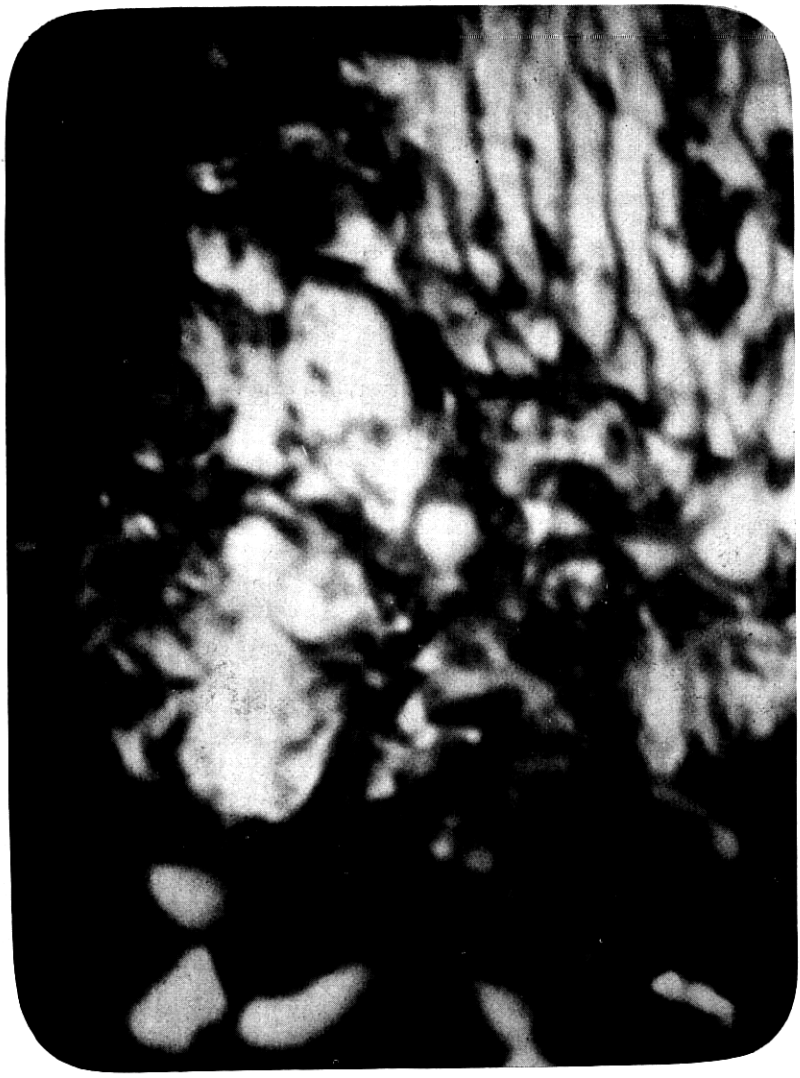


Fig. K. (*continued.*) Under higher magnification one of these patches shows clearly the remaining vestige of laminated structure and the commencement of spheroidization. Magnification 9000 X.

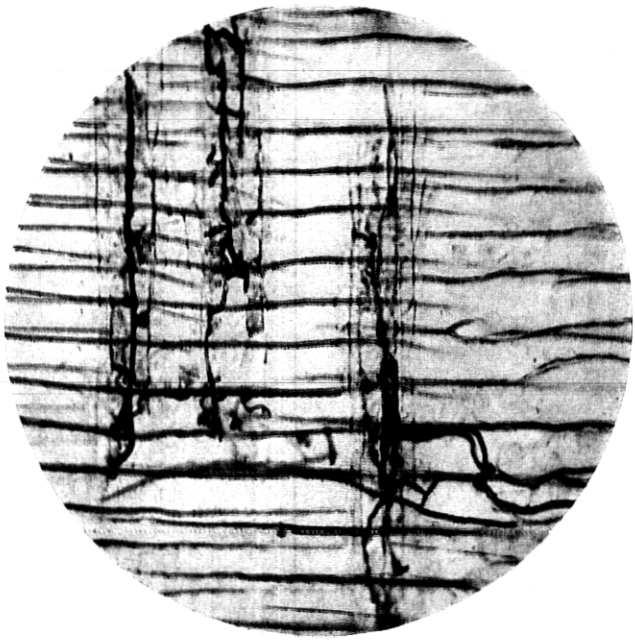


Fig. L. Direct autochrome color reproduction of a stained specimen of Southern Yellow Pine showing sap-stain fungus mycelium. Magnification 100 X. This particular fungus is harmful to the extent that it causes a discoloration of the sapwood, which assumes a blue color in place of the usual straw-yellow. Wood-destroying fungi differ somewhat in their appearance from the one illustrated.

Fig. M. Direct color photomicrography by the autochrome process of a radial section of mahogany wood. Magnification 50 X. Mahogany is one of the best of cabinet woods and finds wide application in the telephone plant.