Optical Metallography

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General Uses

• Imaging of topographic or microstructural features on polished and etched surfaces at magnifications of 1 to 1500×
• Characterization of grain and phase structures and dimensions

Examples of Applications

• Determination of fabrication and heat-treatment history
• Determination of braze- and weld-joint integrity
• Failure analysis
• Characterization of the effects of processing on microstructure and properties

Samples

• Form: Metals, ceramics, composites, and geologic materials
• Size: Dimensions ranging from $10^{-5}$ to $10^{-1}$ m
• Preparation: Specimens are usually sectioned and mounted, ground, and polished to produce a flat, scratch-free surface, then etched to reveal microstructural features of interest

Limitations

• Resolution limit: Approximately 1 µm
• Limited depth of field (cannot focus on rough surfaces)
• Does not give direct chemical or crystallographic information about microstructural features

Estimated Analysis Time

• 30 min to several hours per specimen, including preparation

Capabilities of Related Techniques

• Scanning electron microscopy: Provides better resolution (higher magnifications); greater depth of field (can image rough surfaces); qualitative elemental microanalysis
• Electron probe x-ray microanalysis: Provides quantitative elemental microanalysis
• Transmission electron microscopy: Provides much better resolution (much higher magnifications) on specially prepared specimens; semiquantitative elemental microanalysis; crystallographic information on microstructural features

Introduction

Optical metallography, one of three general categories of metallography, entails examination of materials using visible light to provide a magnified image of the micro- and macrostructure. In scanning electron microscopy (SEM), the second category, the surface of the specimen is bombarded with a beam of electrons to provide information for producing an image (see the article "Scanning Electron Microscopy" in this Volume). Lastly, transmission electron microscopy (TEM) consists of passing a beam of electrons through a very thin specimen and analyzing the transmitted beam for structural information (see the article "Analytical Transmission Electron Microscopy" in this Volume). Microscopy (microstructural examination) involves magnifications of approximately 50× or higher; macroscopy (macrostructural examination), 50× or lower.

Optical microscopy and, occasionally, SEM are used to characterize structure by revealing grain boundaries, phase boundaries, inclusion distribution, and evidence of mechanical deformation. Scanning electron microscopy is also used to characterize fracture surfaces, integrated circuits, corrosion products, and other rough surfaces, especially when elemental microanalysis of small features is desired. Transmission electron microscopy is used to examine dislocation arrangements or structures and other small defects in metals and alloys. Second-phase particles not observable using optical metallography can frequently be analyzed using TEM.

Because the macro- and microstructure of metals and alloys often determine the behavior of the material, characterization of the effects of composition, processing, service conditions, and other such variables on the macro- and microstructure is frequently required. Typical structure-property relationships that have been established using optical metallography include:

• A general increase in yield strength and hardness of a metal with decreasing grain size
• A general tendency for a decreased ductility with increasing inclusion content
• Correlations of weld penetration, heat-affected zone (HAZ) size, and weld-defect density with the nature and character of the welding
**300 / Metallographic Techniques**

- Evaluation of such surface treatments as carburizing and induction hardening by determinations of the depth and microstructural characteristics of the hardened region
- Correlations of fatigue crack growth rates and fracture-toughness parameters with such structural variables as inclusion content and distribution
- Association of failure initiation sites with microstructural inhomogeneities, such as second-phase particles
- Correlations of anisotropic mechanical behavior with elongated grains and/or preferred grain orientations

The microstructures of metals and alloys are determined by composition, solidification processes, and thermomechanical treatment. Therefore, these process variables determine the response of metals and alloys to laboratory and service environments. Because of the relationships between structure and properties, metallographic characterization is used in materials specification, quality control, quality assurance, process control, and failure analysis.

Optical metallography is applicable to studies ranging from fundamental research to production evaluations. This article will discuss use of optical methods to evaluate structure and to relate that structure to process conditions and/or material behavior. Detailed information on the principles and instrumentation of optical microscopy is available in the article “Optical Microscopy” in Volume 9 of the 9th Edition of *Metals Handbook*.

**Specimen Preparation**

The first step in metallographic analysis is to select a sample that is representative of the material to be evaluated. This step is critical to the success of any subsequent study. The second, equally important step is to correctly prepare a metallographic specimen.

The region of the sample that is of interest must be sectioned from the component. For example, if a failure occurred because a steel pipe leaked during service, the metallographic analysis would probably involve at least three samples: one removed from the pipe such that a portion of the leak is contained in the sample, another removed near the leak, and a third taken far from the leak. Each of the samples would be mounted to facilitate handling. Selected surfaces would then be ground flat, polished, and etched to reveal the specific structure or structures of interest.

**Sectioning** of a metallographic sample must be performed carefully to avoid altering or destroying the structure of interest (see the article “Sectioning” in Volume 9 of the 9th Edition of *Metals Handbook*). The most widely used sectioning devices are the abrasive cutoff machine, ranging from units using thin diamond-rimmed wafering blades to those using wheels that are more than 1.5 mm (5/64 in.) thick, 30 to 45 cm (12 to 18 in.) in diameter, containing silicon carbide particles.

Heat is generated during abrasive cutting, and the material just below the abraded surface is deformed. To minimize burning and deformation, a lubricant or coolant is typically used. Wet cutting yields a flat relatively smooth surface. However, because of the abrasion associated with cutting, the structure of the metal or alloy is damaged to a depth of approximately 1 mm (0.04 in.). The exact depth of damage depends on the type of cutoff wheel used, the cutting speed, and the hardness of the specimen. The harder the specimen, the shallower the depth of damage. This damaged layer must be removed by grinding. However, before the specimen can be conveniently ground, it often must be mounted.

**Mounting** facilitates handling of the specimen. A procedure that does not damage the specimen should be selected. Because large specimens are generally more difficult to prepare than small ones, specimen size should be minimized. Standard or typical specimen mounts are right circular cylinders 25 to 50 mm (1 to 2 in.) in diameter. Mounting mediums should be compatible with the specimen regarding hardness and abrasion resistance. Two common mounting materials are thermosetting phenolics, such as Bakelite, and thermoplastic materials, such as methyl methacrylate (Lucite). A thermosetting polymer develops a rigid three-dimensional structure upon being heated and held at 200 to 300 °C (390 to 570 °F). A thermoplastic polymer softens when held at elevated temperatures.

Mounting involves placing the specimen in a mold and surrounding it with the appropriate powders. The mold and its contents are then heated under pressure to the thermal setting or the softening temperature. Once the powder sets, thermosetting mounts can be removed from the mold without lowering the temperature; thermoplastic mounts must be cooled to ambient temperature before removal. Mounting pressure or temperature may alter the structure of low melting temperature or soft and/or fragile specimens; therefore, castable (cold-mounting) techniques have been developed.

Plastics that set at room temperature are referred to as castable (cold-mounting) materials. The most widely used materials are epoxy resins. Epoxies resist acids and strong solvents effectively, a desirable characteristic in any mounting material. Epoxies and thermoplastic materials are relatively soft mounting materials, and the specimen in such a mount must often be surrounded by a hard material, for example, harden steel balls (Fig. 1). This material helps retain the edges of the sample by maintaining a flat surface during grinding and polishing. Additional information on mounting techniques and materials is available in the article “Mounting of Specimens” in Volume 9 of the 9th Edition of *Metals Handbook*.

**Grinding** is generally considered the most important step in specimen preparation. Care must be taken to minimize mechanical surface damage. Grinding is generally performed by the abrasion of the specimen surface against water-lubricated abrasive wheels (assuming water does not adversely affect the metal). Grinding develops a flat surface with a minimum depth of deformed metal and usually is accomplished by using progressively finer abrasive grits on the...
Handbook.

Polishing

Interpretation

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specimen

Fig. 2 The effect of disturbed metal on the metallographic appearance of a plain carbon steel
(a) A layer of disturbed metal—an artifact structure caused by grinding damage—covers the polished surface. (b) The layer of disturbed metal is removed, and the structure is revealed to be lamellar pearlite.

Etched using picral. 1000x

(a) (b)

Fig. 3 The effect of improper polishing on AISI 1010 steel
(a) “Comet tails” from improper polishing. (b) The same material polished correctly, exhibiting small manganese sulfide inclusions

(a) (b)

grinding wheels. A typical sequence might begin with 120- or 180-grit papers and proceed to 240, 320, 400, and 600 grits. Scratches and damage to the specimen surface from each grit must be removed by the next finer grinding step.

The surface damage remaining on the specimen after grinding must be removed by polishing. If this disturbed or deformed metal at the surface is not removed, microstructural observations may be obscured (Fig. 2). Because structure and properties are so closely related, conclusions based on the structure in Fig. 2(a) would lead to incorrect interpretation of the anticipated behavior of the metal. Grinding of metallographic specimens is discussed in the article “Mechanical Grinding, Abrasion, and Polishing” in Volume 9 of the 9th Edition of Metals Handbook.

Polishing of the metallographic specimen generally involves rough polishing and fine polishing. In rough polishing, the cloth covering on a wheel is impregnated with a fine (often as small as 1 µm) diamond paste or a slurry of powdered α-Al2O3 in water, and the specimen is held against the rotating wheel. The cloth for rough polishing is frequently napless, providing easy access of the polishing abrasive to the specimen surface. Fine polishing is conducted similarly, but with finer abrasives (down to 0.05 µm in diameter) on a napped cloth.

Although often automated, polishing can be performed by hand. Vibratory polishing and electropolishing techniques have also been developed for many metals and alloys (see the article “Electrolytic Polishing” in Volume 9 of the 9th Edition of Metals Handbook). Polishing should yield a scratch-free specimen surface, in which inclusions and other second-phase articles may be visible. Polishing damage, such as that illustrated in Fig. 3, should be recognized and avoided when preparing metallographic specimens.

Etching includes any process used to reveal the microstructure of a metal or alloy. Because many microstructural details are not observable on an as-polished specimen, the specimen surface must be treated to reveal such structural features as grains, grain boundaries, twins, slip lines, and phase boundaries. Etchants attack at different rates areas of different crystal orientation, crystaline imperfections, or different composition. The result surface irregularities differentially reflect the incident light, producing contrast, coloration, polarization, etc. Various etching techniques are available, including chemical attack, electrochemical attack, thermal treatments, vacuum cathodic etching, and mechanical treatments (see the articles “Color Metallography” and “Etching” in Volume 9 of the 9th Edition of Metals Handbook). Chemical and electrochemical attack are the most frequently used. The details of the structure revealed by etching depend on the type of etchant used (Fig. 4).

Metallography involves many steps that can obscure or alter the structure observed during examination, leading to erroneous conclusions. Therefore, specimen preparation is not necessarily straightforward, and care must be taken to ensure that the structure observed is not an artifact. Good metallography is necessary in developing a correlation between the structure and the properties of metals and alloys.

Macroanalysis

Macrostructural characterization of metals and alloys is the detailed evaluation of large-scale inhomogeneities in composition, morphology, and/or density. These inhomogeneities may develop during such procedures as casting, extrusion, forging, rolling, and welding or during service. Figure 5 shows the macrostructure of a small relatively pure aluminum ingot exhibiting typical cast grain structure. To obtain the macrograph, the aluminum ingot was sectioned, then ground and polished to produce a flat reflective surface. The polished section was then etched by immersion in a solution that attacked the various grain orientations at different rates.

The etched structure was examined using a low-power microscope. The structural elements visible in this macrograph are grains. The small grains near the bottom of the ingot appear relatively equiaxed. This region of small equiaxed grains is the chill zone. During casting, such macrostructural defects
302 / Metallographic Techniques

Fig. 4 Comparison of nital and picral for revealing a martensite structure
(a) Specimen etched using nital (nitric acid in ethanol or methanol). (b) Specimen etched using picral (picric acid in ethanol). Both 1000 x

Fig. 5 Macrostructure of ass-cast aluminum ingot
Transverse section shows outer chill zone and columnar grains that have grown perpendicularly to the mold faces. Etched using Tucker's reagent. 1.5 x

Fig. 6 Macrostructure of a continuous-cast copper ingot
(a) Spider cracks revealed using dye-penetrant inspection. Transverse section at top; longitudinal section at bottom. (b) Same ingot, etched using Waterbury's reagent. Cracks are not revealed. Both approximately 0.5 x

as gas or shrinkage porosity and center cracks can develop. Many of these defects can be characterized using macrostructural evaluation.

Figure 6(a) shows spider cracks in the center of a copper specimen. This specimen was sectioned, ground, and polished, but not etched. Chemical etching and subsequent evaluation of the macrostructure may fail to reveal this type of structural defect (Fig. 6b).

The cracks shown in Fig. 6(a) were revealed by applying a dye penetrant to the polished specimen. The dye was drawn into the cracks by capillary action, and the surface was then wiped clean. The specimen was then placed under a light that caused the dye to fluoresce, and the cracks became readily observable. Dye-penetrant techniques are excellent for examination of crack-like macrostructural defects in metals. However, grains and other microstructural features are visible only after etching, which frequently obscures the presence of the cracks. Therefore, different metallographic techniques are necessary to reveal various macrostructural elements.

Materials characterization by optical macrostructural examination can be divided into three categories. First, examination of the macrostructure of metallurgically prepared sections removed from the component of interest is used to evaluate such structural parameters as:

- Flow lines in wrought products
- Solidification structures in cast products
- Weld characteristics, including depth of penetration, fusion-zone size and number of passes, size of heat-affected zone and type and density of weld defects
- General size and distribution of large inclusions and stringers
- Fabrication defects, such as laps, cold welds, folds, and seams, in wrought products
- Gas and shrinkage porosity in cast products
- Depth and uniformity of a hardened layer in a case-hardened product

Second, characterization of the macrostructural features of fracture surfaces is used to identify such features as:
incomplete, represents the wide variety of features that can be evaluated and characterized using optical macroscopy. One of the major constraints of optical macroscopy is its limited depth of focus when the surfaces examined are very rough. If this lack of depth of focus is a problem, use of SEM is recommended.

**Macroscopic of Metallographic Sections**

Preparation of a metallographic section for examination requires careful selection of the area to be characterized. This area must be chosen to represent the unique features of a specific zone of interest or the general features of a part or component selected for process characterization or quality assurance. The selected region of the specimen must then be removed from the component using techniques that do not damage or distort the features of interest. The section of interest is then prepared metallographically, and the prepared section is characterized using macroscopic examination.

Macroscopic examination generally does not require the extreme surface smoothness needed for microscopic examinations. Such surface preparation techniques as etching are frequently prolonged such that surface features are greatly enhanced; therefore, quantitative measurements should not be conducted on macroetched samples. Heavy etching accentuates any microstructural inhomogeneity (Fig. 7). The flow lines show the direction of metal flow during processing and frequently represent paths for easy fracture.

Figure 8 shows the use of similar macroscopic techniques to illustrate the depth of case hardening in a tool steel; Fig. 9, for examination of an arc weld. The weld macrograph shows the different etching characteristics of the various areas of the weld. The existence of the HAZ illustrates the effect of welding on the structure. The 2% nital etchant used to reveal the weld macrostructure is much less aggressive than the 50% hydrochloric acid etchants used on the specimens shown in Fig. 7 and 8 and reveals more structural detail.

Macroscopic examination of cast structures can be used to reveal various casting conditions. Solidification patterns are appar-

**Fig. 7 Flow lines in a forged 4140 steel hook**

Specimen was etched using 50% HCl. 0.5 ×

**Fig. 8 Case-hardened layer in W1 tool steel**

Specimens were austenitized at 800 °C (1475 °F), brine quenched, and tempered 2 h at 150 °C (300 °F). Black rings are hardened zones. Etched using 50% hot HCl. Approximately 0.5 ×

**Fig. 9 Section through an arc butt weld joining two 13-mm (0.5-in.) thick ASTM A517, grade J, steel plates**

The schematic shows the fusion zone, the heat-affected zone, and base metal. Etched using 2% nital. 4 ×

- Fracture initiation site
- Changes in crack propagation process

Third, characterization of surfaces and surface defects on parts and coupons is accomplished for purposes such as:

- Estimations of surface roughness, grinding patterns, and honing angles
- Evaluation of coating integrity and uniformity
- Determination of extent and location of wear
- Estimation of plastic deformation associated with various mechanical processes
- Determination of the extent and form of corrosive attack; readily distinguishable types of attack include pitting, uniform, crevice, and erosion corrosion
- Evaluation of tendency for oxidation
- Association of failure with welds, solders, and other processing operations

The above listing of uses for macrostructural characterization of materials, though
ent in the cross sections of macroetched ingots (Fig. 5 and 6). The outer chill zone depth, shape and size of the columnar or dendritic grains perpendicular to the mold wall, and size of the central equiaxed zone in a casting can be established (Fig. 10). One benefit of the macroscopy of cast structures is the ability to reveal the structure and associated defects.

Optical macroscopic examination of a fracture surface may reveal features that will help establish the failure process. For example, Fig. 11 illustrates a fracture in a railroad rail. The relatively smooth region in the photograph represents crack growth because of cyclic or fatigue loading. The dark spot (or fish eye) in the center of the reflective area represents the fracture-initiation site. The remainder of the surface failed by overload. This macroscopic observation of the failed rail shows that the failure was initiated because of the dark-appearing defect in the rail.

The macroscopic nature of many fractures is such that the fracture origin is easily recognizable. Brittle or low-ductility fractures have characteristic V-shaped markings on the fracture surface (Fig. 12) known as chevrons or herringbone marks. The tip of the V generally points to the origin of the failure. The origin of fatigue failures can also be isolated using macroscopic examination. For example, Fig. 13 shows a failure of a steel housing tube initiated in four regions. Each initiation region is observable in the macrographs, as shown by the four arrows. The position of the crack fronts at various times during the failure process is also visible as the so-called beach marks that are initially fairly concentric to the origin. The major problem with optical macroscopic or microscopic examination of fracture surfaces is the technique’s inability to obtain favorable focus over the entire surface if the magnification exceeds 5 to 10×. Therefore, SEM has become a standard metallographic tool in failure analysis.

Macroscopic evaluation of corroded parts can also provide considerable insight into corrosion processes. Each type of corrosion-induced failure causes a characteristic macrographic appearance; therefore, evaluation using optical macroscopy is generally effective. A frequent mistake in failure analysis is to neglect examination of the broken pieces at low magnifications. Too frequently the component is sectioned immediately, and the failure, casting, or other type of specimen examined at high magnification. Optical microscopic evaluation clearly is significant in any structural evaluation, but should not replace characterization by macroscopy.

These two types of metallography are complementary, but examination should always begin at low magnification and work upwards. Detailed information on sample preparation, equipment and etchants used in macroanalysis, and interpretation of results is available in Volume 9 of the 9th Edition of Metals Handbook.

Microanalysis

The importance of microstructure to the properties of metals and alloys has long been recognized. Grain size, twins, and the size, shape, and distribution of second-phase particles are important in determining the behavior of most structural metals. Therefore, characterization of the various microstructural elements in a metal or alloy is often necessary. Process-control parameters are established to provide specific grain sizes. The number, size, and distribution of second-phase particles, such as inclusions, are frequently specified, and quantitative metallographic procedures have been developed to describe microstructure.

The upper limit of useful magnification in the optical microscope is approximately 1500×, and the fundamental limitations of light optic systems limit resolution to features which are ~1 µm or larger. Although this value is small, many microstructural features influencing the properties of metals and alloys are too small to be observed using optical microscopy. Dislocations, numerous
Fig. 13 Fractographs of a typical fatigue crack in a clamp
(a) The fatigue crack origin is marked by the arrow. The crack propagated to the right by continuous fatigue cracking (light) region, then continued alternately by rapid tearing and slow fatigue cracking. 2×. (b) Higher magnification view of the region near the arrow in (a). 10×

Fig. 14 Copper alloy 26000 (cartridge brass, 70%) sheet, hot rolled to a thickness of 10 mm (0.4 in.), annealed, cold rolled to a thickness of 6 mm (0.239 in.), and annealed to a grain size of 0.120 mm (0.005 in.)
At this reduction, grains are basically equiaxed. Compare with Fig. 15. Diagram in lower left of each micrograph indicates orientation of the view relative to the rolling plane of the sheet. Etched using NH₄OH plus H₂O₂. 75×

Fig. 15 Same alloy and processing as in Fig. 14, but reduced 50% by cold rolling from 6 mm (0.239 in.) to 3 mm (0.120 in.)
Grains are elongated in the rolling direction. Diagrams indicate same orientation of view as in Fig. 14. Etched using NH₄OH plus H₂O₂. 75×
types of second-phase particles, spinodal and ordered structures, and many aspects of martensitic structures can be categorized as too small for optical microscopy. Therefore, metallographic observations of these very fine structural features is generally restricted to electron microscopy. Optical microscopy, then, is used primarily to examine grain structures and the morphology of large second-phase particles. Specialized optical metallographic techniques, such as polarized light microscopy and interference microscopy, can add significantly to the information obtained in a microscopic investigation, and interference microscopy can be used to identify height differences on a sample surface that are far smaller than 0.2 μm.

Optical characterization of the microstructures of metals and alloys involves determination of the size and shape of the grains, the extent of twinning, and some of the characteristics of grain boundaries and other observable defects. Solidification, solid-state transformation, deformation, and annealing microstructures are the four basic types in metals and alloys. Each of these has distinct characteristics.

Microstructural features exist in three dimensions, and in a typical metallographic observation, only two dimensions are observed. Therefore, effective microscopy frequently requires microstructural observations in two or more directions. Figures 14 and 15 illustrate the value of viewing the microstructure in several directions. Figure 14 shows an annealed microstructure exhibiting similar grain shapes in all three views. Grain size is characterized by placing a line of known length (or preferably a circle of known circumference) on the magnified image of the microstructure and counting the number of intersections between the line and grain boundaries in the microstructure. The number of intersections, N, can be converted to a measure of grain size, \( d \), using:

\[
d = \frac{L}{NM}
\]  

(Eq 1)

where \( M \) is the magnification of the image.

**Fig. 16 Dendritic solidification structure in a Ni-5Ce (at.%) alloy**

Nickel dendrites (light in b and c) are surrounded by a matrix of nickel-cerium eutectic. (a) 25 ×. (b) 75 ×. (c) 250 ×

**Fig. 17 Typical defects observable using optical microscopy**

(a) Shrinkage porosity in an aluminum alloy 5052 ingot. Note angularity. 50 ×. (b) Coarse primary CrAl₇ crystal in aluminum alloy 7075 ingot. 100 ×. (c) Oxide stringer inclusion in a rolled aluminum alloy 1100 sheet. 250 ×. All as-polished
Specimen along observed, and $L$ is the length of line on the image.

The microstructure of the cold-rolled copper alloy shown in Fig. 15 differs from that of the annealed metal. Rolling elongated the grains in the rolling direction and flattened the grains in directions transverse or normal to the rolling directions. This change can render the grain structure—and the resulting mechanical properties—anisotropic. Because of the interrelationships between grain morphology (size and shape) and mechanical properties, characterization of the grain structure is a typical metallurgical function.

The most commonly observed solidification structure is dendritic. A dendritic structure usually exhibits compositional variations, with the dendrite arms containing less alloying element or impurity than interdendritic regions. Because of such compositional changes (termed coring), the rate of etching at interdendritic regions differs from that at dendrite arms. If the alloying element or impurity content is high, interdendritic regions may develop a two-phase structure (Fig. 16). Because dendrite arm spacing tends to decrease with increasing cooling rates, the properties of as-cast metals depend on the solidification rates.

Most metals shrink during solidification. Therefore, the liquid trapped between dendrite arms during solidification is frequently insufficient to fill the space between the arms when solidification is complete. This inability to fill the remaining space leads to shrinkage porosity, which can be observed microscopically. Porosity is generally easier to observe on as-polished specimens than on polished and etched ones. Figure 17(a) shows a typical example of shrinkage porosity.

Other structural defects, such as inclusions and stringers (Fig. 17b and 17c), can also be observed microscopically in as-polished specimens. Such defects as those shown in Fig. 17 can serve as failure-initiation sites in metals and alloys; therefore, characterization of their size, shape, and distribution is necessary to establish material properties and engineering reliability. Quality-assurance programs frequently require controlling defects to regulate their number, size, and shape in a particular manner. For example, a component having a stringer distribution such as that shown in Fig. 17(c) would have better ductility if specimens or components were tested with the major stresses parallel to the stringer than if specimens were oriented with the major stresses perpendicular to the stringer.

Transformation structures almost always contain two phases. In such structures, the major phase is typically termed the matrix, or base structure, and the minor phase is termed the second phase. The size, shape, and distribution of second-phase particles are important in determining the properties of metals and alloys. Characterization of second-phase morphology can sometimes be accomplished using optical metallography. However, the second phase is sometimes so small that the resolution necessary to characterize the phase morphology exceeds the limits of the optical microscope. In these cases, transmission electron microscopy must be used. Age-hardenable or precipitation-hardened metals and alloys generally must be characterized using electron microscopy.

High-temperature phase transformations frequently nucleate at grain boundaries. The grain-boundary structures can be discrete or continuous. Continuous grain-boundary constituents (Fig. 18) provide easy fracture paths when the grain-boundary phase is less ductile than the matrix phase. For the material shown in Fig. 18, the expected failure would be fracture along the grain-boundary carbides. Figure 19 also shows discrete second-phase precipitates at grain boundaries. Comparison of the microstructures shown in Fig. 18 and 19 reveals differing second-phase morphologies in two similar alloys. Therefore, the properties of these two alloys are also different, with the structure illustrated in Fig. 18 exhibiting the highest strength but the least ductility.

The microscopic details of deformation structures typically cannot be established using optical metallography. Deformation changes number and arrangement of dislocations (crystal defects) in the metal on an atomic scale. This dislocation substructure is best characterized using TEM. Optical metallography can be used to supplement TEM through characterization of the grain size and anisotropy in grain shape and distribution.

Microstructural changes due to annealing may be studied using TEM or optical microscopy. The most important structural changes that occur during annealing are recovery, recrystallization, and grain growth. Recovery is the rearrangement and annihilation of imperfections (primarily vacancies and interstitials) within each grain of a
cold-worked polycrystalline component. Because recovery deals mainly with point defects, any microstructural observations of it are difficult, and optical microscopy cannot be used because of its limited resolution.

Recrystallization is the formation of new strain-free grains within the previously cold-worked (strained) grains. The initial stages of recrystallization occur on such a fine scale that TEM is necessary; however, optical metallography can be readily used to study most of the recrystallization. The size of the recrystallized grains depends on the amount of cold working of the specimen before the recrystallization anneal. The greater the amount of cold work, the finer the grain size (Fig. 20). Because grain boundaries are a crystalline defect, continued annealing will cause this array of grains to be unstable, and grain growth will take place. Grain growth in a recrystallized specimen decreases the grain-boundary surface area to specimen volume ratio because the average grain size increases as grain growth takes place. The rate of grain growth depends on temperature and time. Detailed information on all of these types of structures and on the metallography and microstructures of specific metals and alloys is available in Volume 9 of the 9th Edition of *Metals Handbook*.

**SELECTED REFERENCES**