Characterization of Fe-Based Metals and Alloys

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The Fe-C Equilibrium Phase Diagram
Fe – C Equilibrium Phase Diagram

Fe – 0.003% C, diagram and microstructure (2% nital).
Fe – C Equilibrium Phase Diagram

Fe - 0.20% C, diagram and microstructure (4% picral).
Fe – C Equilibrium Phase Diagram

Fe – 0.40% C, diagram and microstructure, 4% picral.
Fe – 0.60% C, diagram and microstructure, 4% picral.
Fe – C Equilibrium Phase Diagram

Fe – 0.80% C, diagram and microstructure, 4% picral.
Fe – C Equilibrium Phase Diagram

Fe – 1.0% C, diagram and microstructure, 4% picral.
Fe – C Equilibrium Phase Diagram

Fe – 1.20% C, diagram and microstructure, 4% picral.
Casting
Scanning electron microscope view of dendrites on the surface of a type 304 austenitic stainless steel electron-beam melt button (Robinson backscattered electron detector, original at 230X magnification).
Macrostructure of a 5-inch (127 mm) square continuously cast billet of type 430 ferritic stainless steel (Fe – 0.03% C – 0.34% Mn – 0.48% Si – 17.78% Cr – 0.26% Ni – 0.05% Mo – 0.07% Cu). Note the three zones: fine equiaxed grains at the extreme surface, columnar grains at mid-thickness and coarse equiaxed grains in the center. Disc was hot acid etched. Note the crack (which would heal in hot working).
Macrostructure of 7-inch (178 mm) square continuously cast discs of type 316 austenitic stainless steel (Fe < 0.08% C – 17% Cr – 12% Ni – 2.5% Mo) after hot acid etching. Disc cut transverse to the growth direction (strand axis). There is a very thin surface layer of equiaxed grains and the columnar grains go to the center. There is no central equiaxed grain zone. The arrow points to a surface defect.
Eutectic cells in gray cast iron revealed by etching with Klemm’s I reagent and enhanced by using polarized light with sensitive tint. Original at 50X magnification.
Primary alpha dendrites in hypoeutectic gray iron. The specimen was etched with 2% nital.
Shrinkage Cavities

Shrinkage cavities in white cast iron, structure revealed using nital.
Hot Working

Hot working occurs at a temperature that is relatively close to the melting point of the metal or alloy. This temperature is normally well above the normal recrystallization temperature. A homogenization cycle may be used prior to hot working to permit alloy diffusion and enhance chemical homogeneity. Too high a temperature must be avoided so that “burning” or grain-boundary liquation (incipient melting) does not occur. The temperature during the last hot working pass is also important as it controls the grain size in the as-rolled microstructure and may influence problems such as “banding” in steels. If the finishing temperature is low, recrystallization will not occur and the grain structure will be coarse and elongated and will contain residual deformation (dislocations). “Warm” working occurs below the recrystallization temperature.
Microstructure of hot rolled Fe – 0.046% C – 0.36% Mn - <0.01% Si – 0.061% Al carbon steel with a finishing temperature of 1600 °F (871 °C). Note the equiaxed ferrite grains and pearlite patches (top – longitudinal plane, bottom – transverse plane). No deformation is present in the ferrite phase. Etched with 2% nital.
Hot Rolled – 649 °C Finishing Temperature

Microstructure of hot rolled Fe – 0.046% C – 0.36% Mn - <0.01% Si – 0.061% Al carbon steel with a finishing temperature of 1200 °F (649 °C). Note the elongated ferrite grains and small pearlite patches (top – longitudinal plane, bottom – transverse plane). The ferrite grains contain considerable residual deformation. Etched with 2% nital.
Cold Working

Cold working occurs at temperatures below the recrystallization temperature. Typically, it is performed at room temperature. For low-melting point metals and alloys, deformation at room temperature can be above the recrystallization temperature. There are a variety of cold working methods, such as rolling, swaging, extrusion and drawing. Cold worked structures normally exhibit deformed grain structures with considerable slip (bcc and fcc metals) or mechanical twinning (hcp metals).
Cold Rolled Carbon Steel

Microstructure of cold rolled 0.003% carbon steel, 2% nital etch.
Illustration of the influence of the austenitizing temperature on the annealed microstructure of 4140 alloy steel (slow cooled 20 °F/h to 1100 °F), 4% picral.
Normalizing
Influence of the normalizing temperature upon the grain size and microstructure of 1040 carbon steel (2% nital).
Quenched and Tempered Microstructures
Martensitic and tempered martensitic microstructure of 5160 alloy steel (2% nital).
FERRITE

Solid solution of one or more elements in body-centered cubic iron
Ferrite grain boundaries in an interstitial-free sheet steel. Etched with Marshall’s Reagent + HF. Original at 200X.
Ferrite grains in lamination sheet steel revealed using Klemm’s I tint etch. This is a duplex condition where there are much larger grains near the surface. Viewed with polarized light plus sensitive tint.
Duplex grain size condition in a low-carbon sheet steel. This is a case where there are only a few grains that are far larger than the rest of the grains present. Etched with 2% nital.
AUSTENITE

A solid solution of one or more elements in face-centered cubic iron.
Twinned austenitic grain structure of solution annealed, wrought Hadfield manganese steel (Fe – 1.12% C – 12.7% Mn – 0.31% Si) tint etched with Beraha’s sulfamic acid reagent (100 mL water, 3 g potassium metabisulfite and 2 g sulfamic acid) and viewed with polarized light plus sensitive tint. Original at 100X.
Twinned austenitic grain structure of wrought, annealed Fe – 39% Ni color etched with Beraha’s sulfamic acid solution (100 mL water, 3 g potassium metabisulfite, 2 g sulfamic acid) and viewed with polarized light plus sensitive tint. Original at 100X.
RETAINED AUSTENITE

Austenite not converted to martensite during cooling (quenching); the cooling did not reach the martensite finish, $M_f$, temperature.
Martensite (colored) and retained austenite (white) in over-austenitized type W1 carbon tool steel (927 °C – 1 h, water quench, 149 °C – 1 h) tint etched with Beraha’s reagent (100 mL water, 10 g sodium thiosulfate and 3 g potassium metabisulfite). Original at 1000X.
CEMENTITE

A compound of iron and carbon, also called iron carbide, with the approximate formula Fe$_3$C and an orthorhombic crystal structure. Other elements, such as Mn and Cr, will substitute for Fe.
Cementite in white cast iron revealed by etching with 2% nital. The matrix is lamellar pearlite. Original at 1000X.
Microstructure of the as-rolled Fe – 1.31% C – 0.35% Mn – 0.25% Si specimen with the intergranular carbide network clearly visible after etching with alkaline sodium picrate, 90 °C – 60 s. Original at 500X magnification. Note also some intragranular Widmanstätten cementite. A brittle intergranular phase makes the alloy brittle.
EUTECTOID

• An isothermal reversible reaction in which a solid solution is converted into two, or more, intimately mixed solids upon cooling. The number of solid phases is the same as the number of components in the system.

• An alloy of the composition of the eutectoid point on an equilibrium phase diagram.

• A structure formed by a eutectoid reaction.
Coarse pearlitic structure in isothermally annealed (780 °C, 1436 °F – 1 h, isothermally transformed) 1080 steel (Fe – 0.8% C – 0.75% Mn) etched with 4% picral. All of the lamellae are resolvable. Original at 1000X.
Ferrite (white) and pearlite in a hot-rolled Fe – 0.4% C binary alloy. Picral etch.
BAINITE

A metastable aggregate of ferrite and cementite from austenite transformation at temperatures below the pearlite range and above the martensite start, $M_s$, temperature. It appears feathery in the upper range and acicular in the lower range (this description applies best to high-carbon steels).
Upper bainite (dark or outlined) and as-quenched martensite (gray or white) in 5160 alloy steel (Fe – 0.6% C - 0.85% Mn – 0.25% Si – 0.8% Cr) that was austenitized at 830 °C (1525 °F) for 30 min., isothermally held at 538 °C (1000 F°) for 30 sec to partially transform the austenite, and then water quenched (untransformed austenite forms martensite).
Lower bainite (dark) and as-quenched martensite (white/gray) in 5160 alloy steel (Fe – 0.6% C - 0.85% Mn – 0.25% Si – 0.8% Cr) that was austenitized at 830 °C (1525 °F) for 30 min., isothermally held at 343 °C (650 °F) for 20 minutes to partially transform the austenite, and then water quenched (untransformed austenite forms martensite).
MARTENSITE

Generic term for microstructures that form by diffusionless transformation, where the parent and product phases have a specific crystallographic relationship.
MARTENSITE

Alloys where the solute atoms occupy interstitial sites (C in Fe) – martensite is hard and highly strained.

Alloys where the solute atoms occupy substitutional sites (Ni in Fe) – martensite is soft and ductile.
Tempered high-carbon martensite and residual cementite in quenched and tempered type 52100 (Fe – 1% C – 1.5% Cr) bearing steel with a fine prior-austenite grain size. Etched with 2% nital.
Improperly carburized and hardened 8620 (Fe – 0.2% C – 0.75% Mn – 0.55% Ni – 0.5% Cr – 0.2% Mo) revealing excess cementite (left, arrows) near the surface but not further below in the case (right). The carburized case contains coarse plate martensite (dark “needles”) and retained austenite between the martensite. Etched with 2% nital.
Low-carbon, “lath” martensite in an over-austenitized specimen of AerMet 100 (Fe – 0.23% C – 13.4% Co – 11.1% Ni – 3.1% Cr – 1.2% Mo). The grain size was coarsened by the heat treatment (1093 °C, AC, age at 675 °C for 6 h, AC) making it easier to see the lath structure. Etched with aqueous 10% sodium metabisulfite and viewed with polarized light plus sensitive tint. Original magnification was 100X. AerMet is a trademark of Carpenter Technology Corp., Reading, Pennsylvania.
Carburized 8620 Alloy Steel

10% Sodium Metabisulfite  Alkaline Sodium Picrate Boiling

Carburized case with excessive grain boundary carbide (Left: 1000x, Right: 500x).
Core of Carburized 8620 Alloy Steel

Lath martensite in unaffected, hardened core, 2% nital.
Decarburization

Decarburized surface of an as-rolled carbon steel (Fe – 0.11% C – 0.85% Mn – 0.21% Si) with a ferrite-pearlite microstructure. 200x
Graphite – Cast Iron

Graphite is the most stable form of carbon in Fe-based alloys, but it is normally present only in cast irons with high carbon and silicon contents. Graphite may be deliberately formed in certain tools steels, such as Type O6, and it has been observed to precipitate in carbon steel pipe held at elevated temperatures for many years. In cast irons, graphite shape may be controlled to produce a variety of shapes from flakes to nodules.
Flake Graphite – Gray Iron
Pearlitic Gray Iron

Beraha’s CdS Reagent, 500X
Ledeburite in White Cast Iron

Fe – 4.0% C – 0.3% Si – 0.16% Mn – 0.91% Cr etched with Beraha’s sulfamic acid reagent, 500x.
Meteorites

Three basic types:

Hexahedrites – single crystals of ferriet (kamacite)

Octahedrites – two phase structure of ferrite and austenite (kamacite and taenite)

Ataxites – recrystallized, two phase
Microstructure of Gibeon, a fine octahedrite meteorite that fell in Southwest Africa (Fe – 7.93% Ni – 0.41% Co – 0.04% P) tint etched with Beraha’s “10/3” reagent and viewed with polarized light plus sensitive tint. The elongated BCC kamacite (k) grains (ferrite) follow the octahedral planes and the color varies with their orientation. Note the Neumann (N) bands (mechanical twins) in the kamacite due to extraterrestrial collisions. The white films (t) are FCC taenite (austenite) and the cross-hatched patches are plessite (p), a mix of kamacite and taenite. Two types of plessite can be seen.