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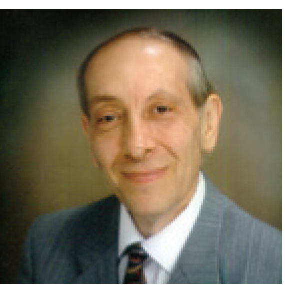
Grain Size and Its Influence on Materials Properties

As metallurgists, we know the importance of grain size, and as heat treaters, we need to be sure we understand how grain size will affect mechanical properties especially when designing our process recipes. Let's learn more.



Grain size specifics

The grain size of carbon and alloy steels is generally understood to mean prior austenitic grain size. On heating steel through its critical range, transformation to austenite takes place. The austenite grains are extremely small when first formed, but grow in size as the time and temperature are increased. The grain size will remain small for steels held at temperatures just above the (upper) critical. At higher temperatures, however, different steels shown wide variation in grain size, depending on chemical composition and steelmaking (deoxidation and prior treatment) practices.

Steels in which elements such as Al and V have been added produce finely-dispersed, not readily soluble and highly refractory carbides or oxides, and maintain a slow rate of grain growth at 925°C (1700°F) and above. Steels without these additions usually develop a relatively large austenitic grain size at temperatures somewhat below this temperature. If you overheat steels with grain refinement additions, such that the fine dispersed phases dissolve or coalesce, then you can end up with a larger grain size than for alloys where these grain refinement additions are not made.

Today, research is underway to find ways to increase carburizing temperatures as high as 1150°C (2100°F) while avoiding excessive grain growth. Microalloying elements such as Al, Nb and Ti have shown considerable promise [1].

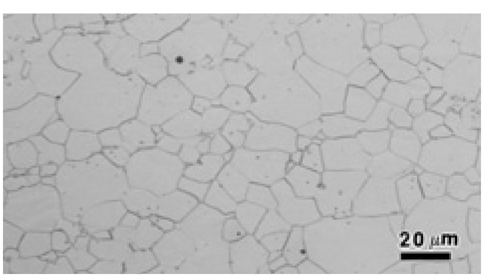


Fig. 1 Ferrite grain structure of a lamination steel; 2%nital etch.

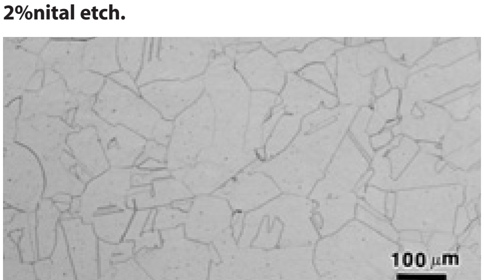


Fig. 2 Austenite grains with annelaing twins in AISI Type 316 stainless steel; Kalling's number 2 etch.

Grain size effect on properties

Grain size has a measurable effect on most mechanical properties. For example, at room temperature, hardness, yield strength, tensile strength, fatigue strength and impact strength all increase with decreasing grain size. Machinability is also affected; rough machining favors coarse grain size while finish machining favors fine grain size. The effect of grain size is greatest on properties that are related to the early stages of deformation. Thus, for example, yield stress is more dependent on grain size than tensile strength [2, 3].

Fine-grain steels do not harden quite as deeply and have less tendency to crack than coarse-grain steels of similar analysis. Also, fine-grain steels have greater fatigue resistance, and a fine grain size promotes a somewhat greater toughness and shock resistance. Steels made fine grained by addition of aluminum have machinability inferior to those made without aluminum. Also, cold working frequently alters grain size by promoting more rapid coarsening of the grains in critically stressed areas. The original grain size characteristics, however, can usually be restored by stress relieving. Coarse-grain steels have better creep and stress rupture properties because diffusion at high temperatures is impeded by subgrain low-angle boundaries present in coarse-grain steels [4].

Measuring grain size

Grain size can be measured using an optical microscope on a transverse metallographic mount (because rolling elongates the grains) by counting the number of grains within a given area, by determining the number of grains that intersect a given length of a random line, or by comparison with reference pictures (standards). Grain size can range from 00 to 14.0 (0.5080 to 0.0028 mm) according to ASTM E112-96(2004). For coarser structures, the number of grains can be counted manually within a certain area, and then calculating the grain size. In measuring austenitic grain size, the time and temperature must be constant to produce reproducible results.

The characteristics of the individual grains also add to the complication of measurement. First, the three-dimensional size of the grains is not constant and the sectioning plane cuts through the grains at random. Thus, on any cross section, a range of sizes is observed, none larger than the cross section of the largest grain sampled. Grain shape also varies, particularly as a function of grain size.

Remember that grain size measurement is also complicated by the different types of grains that can be present in metals, although their fundamental shapes are the same. In body-centered cubic (BCC) metals, such as Fe, Mo, and Cr, we have grains produced in ferritic structures (Fig. 1); in face-centered cubic (FCC) metals, such as Al, Ni, Cu, and certain stainless steels, we have grains produced in austenitic structures (Fig. 2). The grains have the same shapes and are measured in the same way, but we must be careful in describing what kind of grains are being measured.

For example, in the FCC metals, there may be so-called twin boundaries within the grains, produced by annealing or deformation. Twins are ignored if trying to define the grain size. However, if trying to establish a relationship between microstructure and properties (strength, for example), twin boundaries must be taken into consideration as they influence dislocation movement, just as grain boundaries do. There also are pearlite packet boundaries in steels. Therefore, we must recognize the intent of the work being performed.

A number of standard measurement methods can be used (Table 1), and it is important to recognize that all of them are very subjective. Software has been developed to help make grain measurement and counting easier (although it still is necessary to understand what you are trying to measure to ensure representative results). Automated systems usually use simple menus and easy "wizard" guides; use vertical, horizontal, concentric circle or diagonal line intercept methods; perform calculations according to ASTM standards; calculate average grain size from multiple images; and manually add or remove points.

ASTM standards

ASTM International (www.astm.org) has a number of standards for determining the grain size of various materials. For steels, E112-96(2004): Standard Test Methods for Determining Average Grain Size applies. ASTM standards have also been introduced to deal with particular situations including:

- E930-99: Standard Test Methods for Estimating the Largest Grain Observed in a Metallographic Section, (ALA Grain Size) to handle the measurement of occasional very large grains present in an otherwise uniform, fine grain size dispersion
- E1181-02: Standard Test Methods for Characterizing Duplex Grain Sizes or for rating the grain size when the size distribution is not normal; for example, bimodal or duplex steels
- E1382-97(2004): Standard Test Methods for Determining Average Grain Size Using Semiautomatic and Automatic Image Analysis.

A lower ASTM grain size number means the greater the number of grains, as shown in the following table.

ASTM grain size in terms of the number of grains

ASTM grain size number	Number of grains/in.^{2} (mm^2) at 100×
1	Up to 1-1/2
2	1-1/2 - 3
3	3 - 6
4	6 - 12
5	12 - 24
6	24 - 48
7	48 - 96
8	96 and over

There also is an equation expressing the relationship between grain size and yield strength. Bending fatigue also follows a similar relationship. **IH**

Table 1 Test methods to determine grain size

Test method	Description	Comments
Fracture method	Visual examination of fracture surfaces	Works well assuming you have both a material that fails in an intergranular mode and a set of comparative blocks. Analysis of the fracture surface via SEM is excellent and indicates actual prior austenite grain size.
McQuaid-Ehn test	Carburize at 1700˚F (925˚C) 8 hr, cool slowly to allow proeutectoid cementite to mark the grain boundaries	Cementite covers well, but only in small areas of the sample.
Outlining (ferrite) method	Slow cooling hypoeutectoid steels outlines austenite grain boundaries with ferrite	Ferrite does not cover that well and grows quickly.
Oxidation method	Preferential oxidation of austenite grain boundaries	Surface limited
Quench method	Quenching produces partially hardened zone wherein the former austenite grains consist of martensite surrounded by a small amount of fine pearlite.	Surface limited
Special etching techniques	Develops contrast between martensite grains of the same size as the austenite grains prior to quenching.	Etching shows actual prior austenite grain size, but is difficult to control. Only certain grades/carbon levels work, and there is an art to the etching and rating.
Vacuum grooving	Preferentially evaporates austenite grain boundaries	

References

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Additional related information may be found by searching for these (and other) keywords/terms via BNP Media LINX at www.industrialheating.com: grain size, grain refinement, austenitic grain size, fine grain, coarse grain, subgrain, ASTM grain size number, grain size measurement.