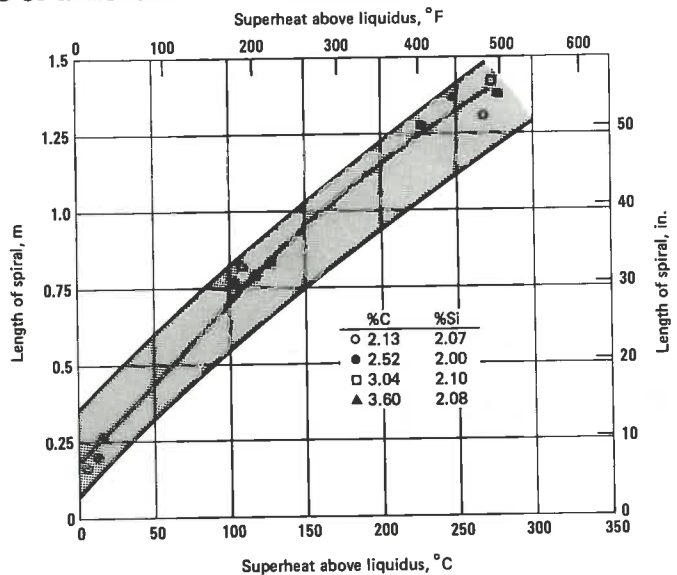Fig. 1 Fluidity versus degree of superheat for four gray irons of different carbon contents

The significance of the relations among fluidity, carbon content and pouring temperature becomes apparent when it is realized that the gradation in strength in the ASTM classification of gray iron is due in large part to differences in carbon content (about 3.60 to 3.80% for class 20; about 2.70 to 2.95% for class 60). The fluidity of these irons thus resolves into a measure of the practical limits of maximum pouring temperature as opposed to the liquidus of the iron being poured. These practical limits of maximum pouring temperature are determined largely by two factors: (a) the ability of both mold and cores to withstand the impact of molten iron, an ability that decreases as the pouring temperature increases, thereby favoring low pouring temperatures; and (b) the fact that metal tap temperatures seldom exceed 1550 °C (2825 °F). Since ladling and reladling to the point of pouring generally accounts for temperature losses of 55 to 85 °C (100 to 150 °F), the final pouring temperatures seldom exceed 1450 to 1495 °C (2640 to 2720 °F), and in most instances maximum pouring temperatures in the range 1410 to 1450 °C (2570 to 2640 °F) are considered more realistic. Table 1 illustrates how, because of differences in liquidus temperature, the amount of superheat (and therefore fluidity) varies with carbon content when various compositions are cast from the same pouring temperature.

Microstructure

The usual microstructure of gray iron is a matrix of pearlite with graphite flakes dispersed throughout. Foundry practice can be varied so that nucleation and growth of graphite flakes occur in a pattern that enhances the desired properties. The amount, size and distribution of graphite are important. Cooling that is too rapid may produce "mottled iron", in which carbon is present in the form of both primary cementite (iron carbide) and graphite. Very slow cooling of irons that contain large percentages of silicon and carbon is likely to produce considerable ferrite as well as pearlite throughout the matrix, together with coarse graphite flakes.

Flake graphite is one of seven types (shapes or forms) of graphite estab-

Table 1 Superheat above liquidus for 2% Si irons of various carbon contents poured at 1455 °C (2650 °F)
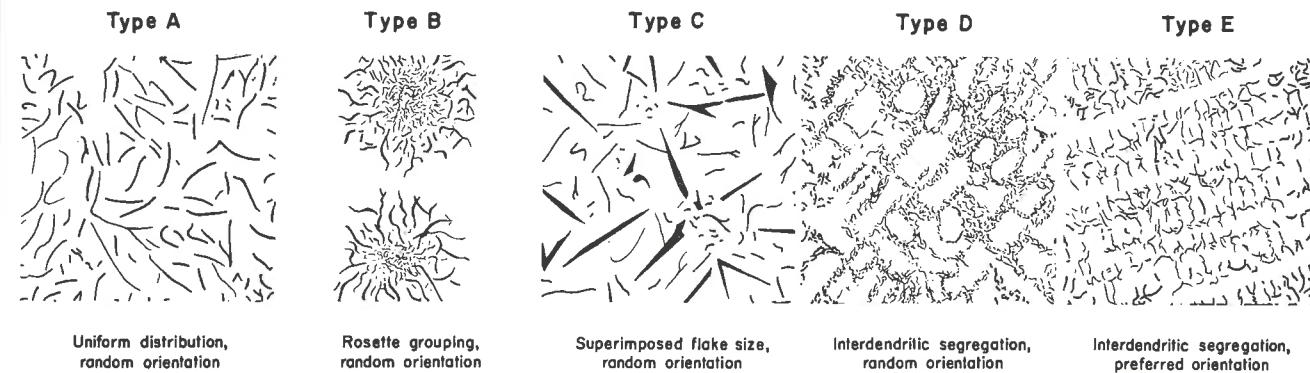
Carbon, %	Liquidus temperature °C	°F	Superheat above liquidus °C	°F
2.52	1295	2360	160	290
3.04	1245	2270	210	380
3.60	1175	2150	280	500

lished in ASTM A247. Flake graphite is subdivided into five types (patterns), which are designated by the letters A through E (see Fig. 2). Graphite size is established by comparison with an ASTM size chart, which shows the typical appearances of flakes of eight different sizes at 100× magnification.

Type A flake graphite (random orientation) is preferred for most applications. In the intermediate flake sizes, type A flake graphite is superior to other types in certain wear applications such as the cylinders of internal-combustion engines. Type B flake graphite (rosette pattern) is typical of fairly rapid cooling, such as is common with moderately thin sections (about 10 mm, or ⅜ in.) and along the surfaces of thicker sections, and sometimes results from poor inoculation. The large flakes of type C flake graphite are typical of kish graphite that is formed in hypereutectic irons. These large flakes enhance resistance to thermal shock by increasing thermal conductivity and decreasing elastic modulus, both of which reduce thermal stress. On the other hand, large flakes are not conducive to good surface finishes on machined parts or to high strength or good impact resistance. The small, randomly oriented interdendritic flakes in type D flake graphite promote a fine machined finish by minimizing surface pitting, but it is difficult to obtain a pearlitic matrix with this type of graphite. Type D flake graphite may be formed near rapidly cooled surfaces or in thin sections. Frequently, such graphite is surrounded by a ferrite matrix, resulting in soft spots in the casting. Type E flake graphite is an interdendritic form, that has a preferred rather than a random orientation. Unlike type D graphite, type E graphite can be associated with a pearlite matrix, thus producing a casting whose wear properties are as good as a casting containing only type A graphite in a pearlitic matrix. There are, of course, many applications in which flake type has no significance as long as the mechanical-property requirements are met.

Solidification of Gray Iron. In a hypereutectic gray iron, solidification begins with the precipitation of kish graphite in the melt. Kish grows as large, straight, undistorted flakes or as very thick, lumpy flakes, which tend to rise toward the surface of the melt because of their low relative density. When the temperature has been lowered sufficiently, the remaining liquid

Fig. 2 Types of graphite flakes in gray iron (AFS-ASTM)

Type A — Uniform distribution, random orientation
Type B — Rosette grouping, random orientation
Type C — Superimposed flake size, random orientation
Type D — Interdendritic segregation, random orientation
Type E — Interdendritic segregation, preferred orientation

In the recommended practice (ASTM A247), these charts are shown at a magnification of 100X. They have been reduced to one-third size for reproduction here. This figure may be purchased from ASTM at a nominal fee.

solidifies as a eutectic structure of austenite and graphite. Generally, eutectic graphite is finer than kish graphite.

In hypoeutectic iron, solidification begins with formation of proeutectic austenite dendrites. As the temperature falls, the dendrites grow and the carbon content of the remaining liquid increases. When the increasing carbon content and decreasing temperature reach eutectic values, eutectic solidification begins. Eutectic growth from many different nuclei proceeds along crystallization fronts that are approximately spherical. Ultimately, the eutectic cells meet and consume the liquid remaining in the spaces between them. During eutectic solidification, the austenite in the eutectic becomes continuous with the dendritic proeutectic austenite, and the structure can be described as a dispersion of graphite flakes in austenite. After solidification, the eutectic cell structure and the proeutectic austenite dendrites cannot be distinguished metallographically except by special etching or in strongly hypoeutectic iron.

With eutectic compositions, obviously, solidification takes place as the molten alloy is cooled through the normal eutectic temperature range, but without prior formation of a proeutectic constituent.

Room-Temperature Structure. On cooling from the eutectic temperature, the austenite will decompose by first precipitating some of the dissolved carbon and then, at the eutectoid temperature, by undergoing complete

transformation. The actual products of the eutectoid transformation depend on rate of cooling as well as on composition of the austenite, but under normal conditions the austenite will transform either to pearlite or to ferrite plus graphite.

Transformation to ferrite plus graphite is most likely to occur with (a) slow cooling rates, which allow more time for carbon migration within the austenite; (b) high silicon contents, which favor the formation of graphite rather than cementite; (c) high values of carbon equivalent; and (d) the presence of fine undercooled (type D) flake graphite. Graphite formed during decomposition is deposited on the existing graphite flakes.

When carbon equivalent values are relatively low or when cooling rates are relatively fast, transformation to pearlite is favored. In some instances, the microstructure will contain all three constituents—ferrite, pearlite and graphite. With certain compositions, especially alloy gray irons, it is possible to produce a martensitic matrix by oil quenching through the eutectoid transformation range. This treatment often is given deliberately in a secondary heat treatment where high strength or hardness is especially desired, such as in certain wear applications. Secondary heat treatment of gray iron castings is of great value in producing components that must be hard, but where machining requirements prohibit the use of components that are cast to final shape in white iron.

Section Sensitivity

In practice, the minimum thickness of section in which any given class of gray iron may be poured is more likely to depend on the cooling rate of the section than on the fluidity of the metal. For example, although a plate 300 mm square by 6 mm thick can be poured in class 50 as well as in class 25 iron, the former casting would not be gray iron, because the cooling rate would be so rapid that massive carbides would be formed. Yet it is entirely feasible to use class 50 iron for a diesel engine cylinder head that has predominantly 6-mm wall sections in the water jackets above the firing deck. This is simply because the cooling rate of the cylinder head has been reduced by the "mass effect" resulting from enclosed cores and the proximity (often less than 12 mm) of one 6-mm wall to the other.

Thus the shape of the casting has an important bearing on the choice of metal specification.

It should be recognized that the smallest section that can be cast gray, without massive carbides, depends not only on metal composition but also on foundry practices. For example, by adjusting silicon content or by using graphitizing additions called inoculants in the ladle, the foundryman may decrease the minimum section size for freedom from carbides for a given basic composition of gray iron.

The mass effect associated with increasing section thickness or decreasing cooling rate is much more pro-