

Effect of Cooling Rate on Eutectic Cell Count, Grain Size, Microstructure, and Ultimate Tensile Strength of Hypoeutectic Cast Iron

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This article describes a series of microstructural and strength studies performed on hypoeutectic cast iron, which was sand cast using a variety of end chills (metallic, nonmetallic, water-cooled, and subzero, respectively). The effects of cooling rate on the eutectic cell count (ECC), grain size, and the ultimate tensile strength (UTS) were evaluated. Attempts were also made to explain these effects and to correlate the UTS with ECC. It was found that subzero chilled and water-cool, chilled cast iron exhibit severe undercooling compared to normal sand cast iron. It was concluded from this investigation that nucleation conditions are completely altered but growth conditions prevail as usual. Therefore, undercooling during solidification is considered to be responsible for variation in ECC, grain size, microstructure, and tensile strength.

Keywords cast iron, gray iron, mold cooling, subzero chill

1. Introduction

1.1 Chilled Cast Iron

Chilled cast iron belongs to a group of metals possessing high strength, high hardness, high toughness, and high wear resistance (Ref 1-2). There is sufficient information available on eutectic cell count (ECC), grain size, microstructure, mode of solidification, and mechanical properties of ordinary cast iron cast in sand molds. However, there is a dearth of information on ECC, grain size, microstructure, mode of solidification, and effects of these properties on the strength of chilled cast iron using various types of chills including water-cooled and subzero chills. The basis of this article is a series of experiments conducted to determine the effect of ECC and solidification on the strength of various types of chilled cast iron. The reason for selecting this series of chilled cast iron for the present investigation is that a wide range of ultimate tensile strength (UTS) values can be obtained with different ECCs. Moreover, using such a chilling technique, a low grade cast iron can be converted into one of the superior qualities depending on the mode of solidification and the ECC.

1.2 Effect of Cooling Rate during Solidification

In general, high cooling rate in castings is largely governed by the design and thermal nature of the casting procedure. One significant factor is the mold material. Metal molds generally offer greater chilling effect on the solidifying mass due to higher heat diffusivity. The influence of higher cooling rates is normally responsible for the superior properties of chilled castings. The use of chills favors refinement of microstructure and steepens the temperature gradient, making solidification directional. The influence of very high cooling rates in producing fine structures offers the possibility for the future development of cast irons possessing high strength and good wear resistance. The undercooling of a melt to a lower temperature increases the number of effective nuclei relative to the growth rate, the latter being restricted by the rate at which the latent heat of crystallization can be dissipated. Conversely, slow cooling favors the growth from few nuclei and produces coarse grain structures. The refining effect of enhanced cooling rate applies both to primary grain size and to substructure, although in the latter case the effect is on the growth process rather than on nucleation. Thus, there is a marked effect upon cell size, grain size, and microstructure when the cooling rate varies over a wide range.

Copper was selected as an important alloying element for hypoeutectic cast iron because of its tremendous potential as a grain refiner. Thus, the present study was planned for the following purposes: (a) to obtain experimental data for the ECC with various cooling rates, (b) to analyze the data in the light of the solidification process, and (c) to correlate the UTS with the ECC.

1.3 Microstructure of Cast Iron

The mechanical properties of a metal depend very much on microstructure. This is especially true for cast iron. The structure depends on the interaction between the effects of the elements present and the cooling rate during and after solidification in the mold (Ref 3). The properties of cast iron are affected mainly by the structure of the austenite dendrites, type of graphite flakes, and the eutectic cells. Several properties of cast iron that are of interest to foundrymen include tensile strength, fracture toughness, wear resistance, hardness, etc. These properties are influenced mainly by chemical composition, alloying elements added, and microstructural features, including graphite type and size and ECC. It is well known that the composition of iron determines the quantity and character

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of the graphite and the metallurgical characteristics of the metallic matrix for some specified set of cooling conditions (Ref 4).

Cooling curves of cast iron have been successfully used to explain gray (stable) and white (unstable) iron solidification as well as the influence of alloying elements (Ref 5, 6). Significant undercooling reflects an absence of nuclei and their ability to serve as eutectic cell centers.

Baker (Ref 7) in his investigation on a fracture mechanics study of gray cast iron observed that both the tensile strength and fracture toughness of cast iron decreased linearly with increasing eutectic cell size (which decreases the cell count). Suzuki and Kayama (Ref 8) concluded from their investigation that confirmation of graphite nucleation out of residual graphite is by means of eutectic cells, and eutectic cell number is an index of nucleation frequency. De Hoff and Rhines (Ref 9) developed an equation to calculate the eutectic cell per unit volume and concluded that this mainly depends on eutectic cell per unit area and the mean diameter of eutectic cells. Fedriksson and Hillert (Ref 10) studied the graphite precipitation in an alloyed cast iron under controlled solidification at various rates. Nucleation of the eutectic liquid can be a difficult process because considerable undercooling is often observed before solidification begins. If the stable eutectic is not nucleated, then the iron may undercool and solidify to form iron carbides mixed with austenite. Therefore, minimum eutectic temperature can be used as a measure of undercooling, and this reflects the amount of primary austenite precipitated and the chilling tendency of the iron. Austenite dendrite interaction was shown to be a major factor in determining the tensile strength of irons (Ref 11).

The most important fact regarding cell structure is that it develops after the precipitation of austenite dendrites. Thus, cell growth conforms to and is superimposed on a dendritic structure that solidifies first. The dendritic structure that solidifies hosts the cells and therefore can have a major effect on cell nucleation and growth (Ref 12). Ruff and Wallace (Ref 13) showed that, by increasing the eutectic cell count, the effective span and stress concentration effect of the graphite can be reduced and hence, an improvement in the tensile strength. A suggested classification of cell size has been studied in detail by Dawson and Oldfield (Ref 14).

1.4 Tensile Strength of Cast Iron

It is generally acknowledged that most of the mechanical qualities of cast iron can be best represented by its tensile strength. Because cast iron is a very brittle material, its yield strength in practice can be taken as equal to its ultimate tensile strength. Optimum tensile strengths can be obtained in cast iron by increasing the amount of graphite-free area (in most cases, primary austenitic dendrites), refining eutectic cell size, and establishing the pearlitic matrix (Ref 15, 16). Treating the base metal with commercial inoculants and neutralizing certain elements, which inhibit graphite nucleation, can result in the formation of more eutectic cells (Ref 17).

Table 1 Chemical composition of the cast iron tested

Element	Composition, wt%
C	3.42
Si	1.8
Cu	1.5
Mn	0.41
S	0.04
P	0.08
Fe	bal

1.5 Past Research

The effect of chills on the solidification characteristics of cast iron has been studied by Bishop et al. (Ref 18). Berry (Ref 19) showed the importance of the solidification time of castings. The eutectic solidification starts at certain locations and continues by radial growth with the simultaneous separation of graphite and austenite from the melt. Furthermore, the lower the temperature of formation (i.e., the greater the amount of under cooling), the finer the graphite formed.

Austenite dendrites interaction was shown to be a major factor affecting the UTS of the material (Ref 20). Hemanth et al. (Ref 21) concluded from their findings that the decrease in the dendrite arm spacing with an increase in the cooling rate was explained by the fact that there is insufficient time available for the diffusion of the solute. The influence of changes in the structure of austenite dendrite, graphite flakes, and eutectic cells on the mechanical properties of the material was investigated by Ruff and Wallace (Ref 22). Sun and Loper (Ref 23) showed that intensive supercooling (both constitutional and thermal) in front of the chilling interface results in the development of cellular dendrite of the graphite into a form recognized as exploded graphite. The morphology of the exploded graphite depends on the compositional and thermal conditions present in front of the interface.

The microstructure of gray and ductile irons is determined by the cooling rate, composition, nucleation, and growth conditions prevailing during solidification and the transformation behavior of austenite during cooling through the critical temperature range (Ref 24). The dendritic structure in cast irons can be significantly refined by selected additions to the melt. The effect of this refinement is to increase the number of grains and to reduce the spacing of the dendrite arms (Ref 25).

1.6 Relevance of This Research

Cast iron has the potential to replace other material in many significant engineering applications. The requirements concerning safety and reliability are always increasing, and therefore, the effect of ECC, grain size, and microstructure on tensile strength is ever more crucial when cast iron is chilled using various types of metallic and nonmetallic chills, including water cool and subzero chills. The present research is intended to fill this void of published data on this topic.

2. Experimental Procedure

2.1 Fabrication of the Material

A cast iron alloy of the composition shown in Table 1, cast using different types of chills, was produced by casting at 1440 °C in the form of ingots (designated as alloys A, B, C, and D, as shown in Table 2). Apart from the usual alloying elements such as silicon, manganese, sulfur, and phosphorus, copper was also added to improve machinability as well as to act as a grain refiner.

2.2 Casting Procedure

The molds for plate-type castings (225 by 150 by 25 mm, AFS standard) were prepared using silica sand with 5% bentonite as a binder and 5% moisture. The melts were carried out using a medium frequency, coreless induction furnace. A base metal analysis, generally 3.42% C and 1.8% Si, was produced and superheated to 1500 °C prior to tapping into a preheated 20 kg capacity handshank. Prior to pouring an inoculation addition (ferro-silicon to promote uniform structure), other alloying elements were stirred into the molten metal using a graphite spoon. The treated metal was poured directly into the mold at a pouring temperature of 1450 °C, which was cooled from one end by a chill set in the mold, in which either water or liquid nitrogen (at –60 °C) was circulated, as shown in Fig. 1. The same type of mold was used for the other alloys, except that no liquid nitrogen/water was passed through the chills. In the case of water-cool chilling and subzero chilling, arrangements were made in the copper chill to circulate water (at 25 °C) and liquid nitrogen (at –60 °C), respectively. This type of casting production routine resulted in chilled cast iron of consistent chemical analysis.

2.3 Microstructural Examination

The specimens for microstructural and strength studies were taken along the length of the casting. Microstructural studies were conducted on finely polished specimens using a scanning electron microscope and a Neophot-21 optical microscope under different magnifications. Various etchants were tried, but nital (2%) proved to be the best and was therefore used.

Grain size measurements were taken from polished specimens using the ASTM index method, and ECC measurements were taken from polished specimens at low magnification (5×) using Steads reagent as the etchant. Tensometer specimens

Table 2 Ultimate tensile strength and microstructure (at chill end) of castings chilled using various chills

Alloy	Chill used	Ultimate tensile strengh, MPa	Microstructure, %
A	Silicon-carbide	289.44	8% cementite in pearlite, 8
B	Steel	306.46	30% cementite in pearlite, 30
C	Water-cool	332.23	55% cementite in pearlite, 55
D	Subzero	355.89	70% cementite in pearlite, 70

Table 3 Eutectic cell count for different alloys along the length of the casting

Specimen location, distance from chill mm	Cells/cm^2 Alloy A	Alloy B	Alloy C	Alloy D
25	85	128	165	185
75	75	104	150	175
125	73	94	106	105
175	70	77	94	95
225	74	84	101	103

Sand casting of the same cast iron (without chill) possesses a eutectic cell count of 72 cells/cm^2 along the length of the casting. 5×

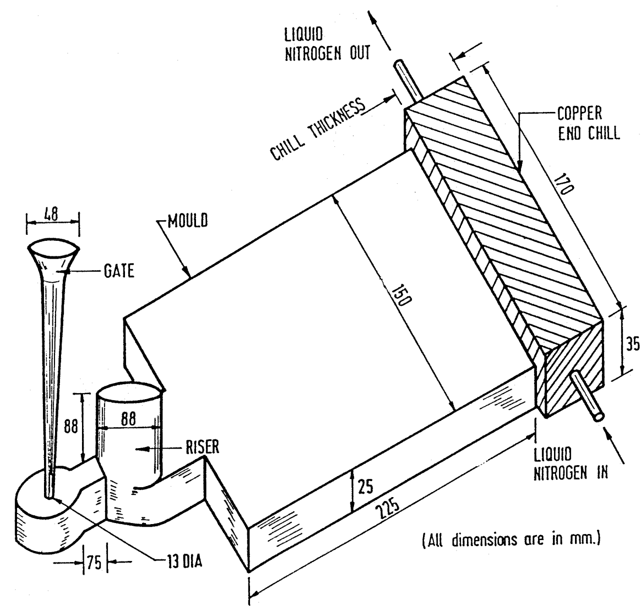

Fig. 1 Mold for producing chilled cast iron

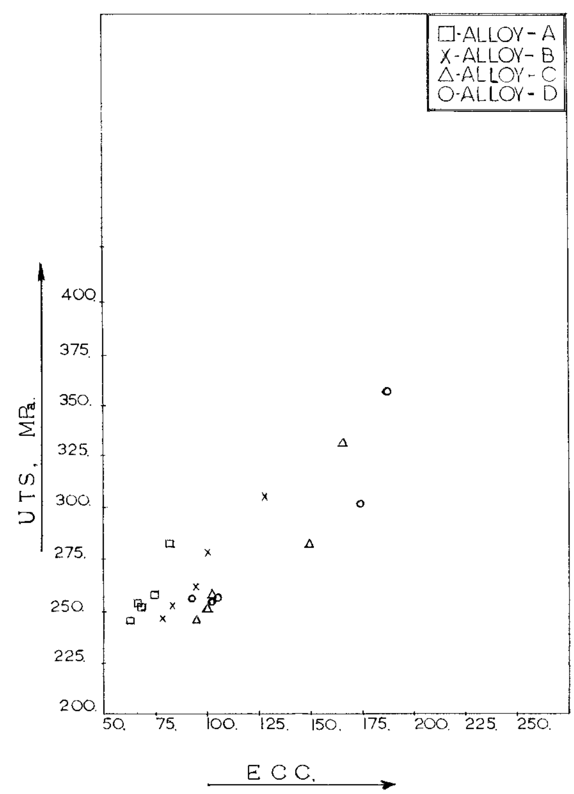

Fig. 2 Relationship between ultimate tensile strength and eutectic cell count for different alloys

were prepared for strength testing (using an Instron testing machine) and the tests were performed in conformance with American Foundryman's Society (AFS) standards.

3. Results and Discussions

Table 2 shows the experimental results of the strength tests conducted on castings using various chills (each 25 mm thick) as well as the microstructures observed. To show the typical relationship between the ECC and the UTS along the length of the casting from the chill end to the riser end, the values for various alloys, A, B, C, and D, are listed in Tables 2 and 3.

3.1 Solidification Structures of Graphite and Eutectic Cells

Solidification of hypoeutectic cast iron begins with the crystallization of primary graphite. The primary graphite develops as straight graphite plates with some branching growing while totally surrounded by liquid. The composition of the remaining liquid shifts toward the eutectic where the liquid is believed to solidify in a manner similar to that of the eutectic, although the primary graphite may influence the size of the eutectic cell and the distribution of the eutectic graphite.

It is generally accepted that the ECC is an indication of the number of nuclei on which solidification has proceeded. Microphotographs of eutectic cells for sand cast (without chill), silicon carbide chilled, steel chilled, water-cool chilled, and subzero chilled cast iron are shown in Fig. 3 to 7, respectively.

The number of nuclei available for solidification of subzero chilled cast iron is higher than the number of nuclei available for water-cool, chilled cast iron, but there is a smaller effect for sand cast iron without a chill. In other words, the nucleation conditions for subzero and water-cool, chilled cast iron are completely different from that of sand cast iron without a chill, with the surprising fact for this variation being the undercooling effect due to chilling. Perhaps the most important fact to recognize regarding cell structure is that it develops after the precipitation of austenite dendrite structure that solidifies first. The dendritic structure hosts the cells and, therefore, can have a major effect on cell nucleation and growth.

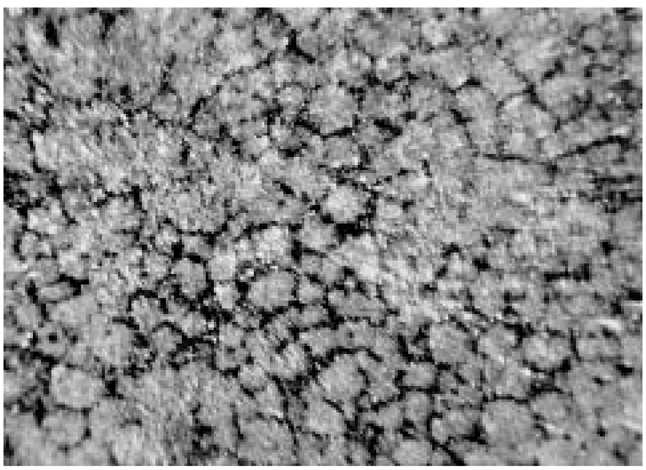

Fig. 3 Micrograph indicating eutectic cells for alloy A (cast with silicon-carbide end chill). 500×

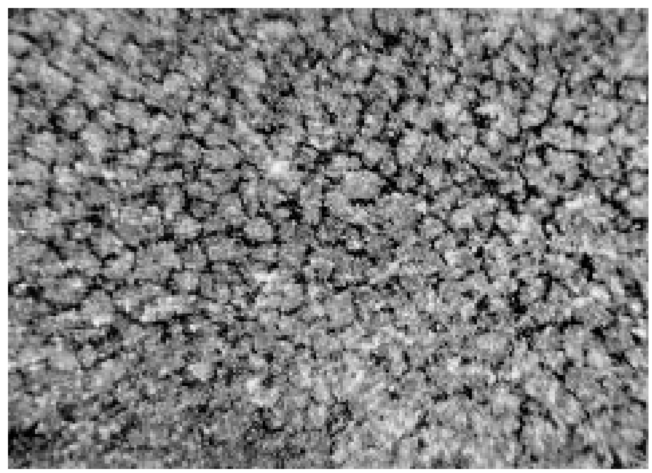

Fig. 4 Micrograph indicating eutectic cells for alloy B (cast with steel end chill). 500×

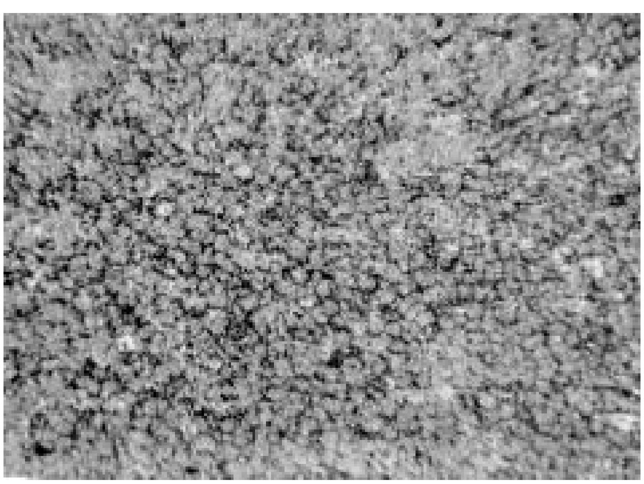

Fig. 5 Micrograph indicating eutectic cells for alloy C (cast with water-cool end chill). 500×

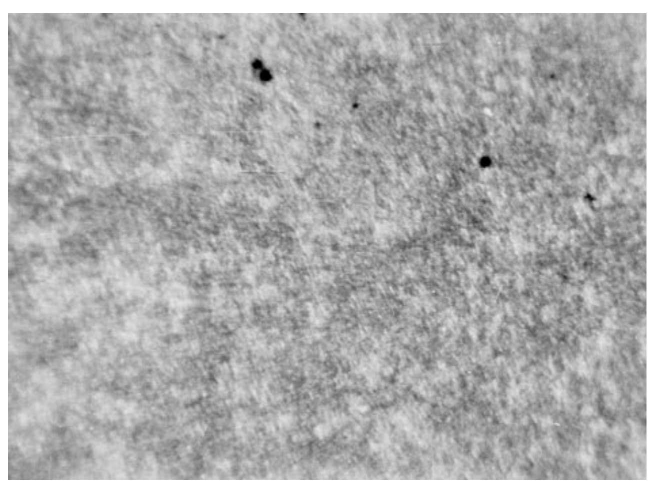

Fig. 6 Micrograph indicating eutectic cells for alloy D (cast with subzero end chill). 500×

The differences in associated graphite, randomness, length, and matrix structure for various alloys, are shown in Fig. 8 to 12. Fast cooling produces fine and highly oriented dendrites, while slow cooling produces large and coarse dendrites. Therefore solidification over a temperature range is the primary requirement for dendrite growth. Primary austenite dendrites readily grow from the liquidus down to the eutectic temperature. Growth of dendrites may also continue concurrently with

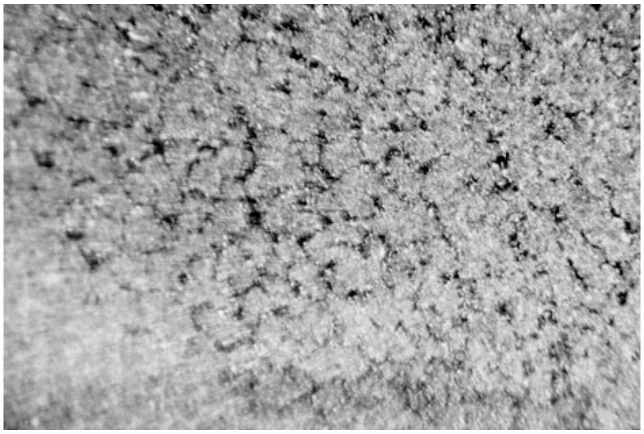

Fig. 7 Micrograph indicating eutectic cells of sand cast specimen (cast without chill). 500×

Fig. 8 Microstructure of alloy A near chill end (cast with silicon-carbide end chill). 500×

Fig. 9 Microstructure of alloy B near chill end (cast with steel end chill). 500×

Fig. 10 Microstructure of alloy C near chill end (cast with water-cool end chill). 500×

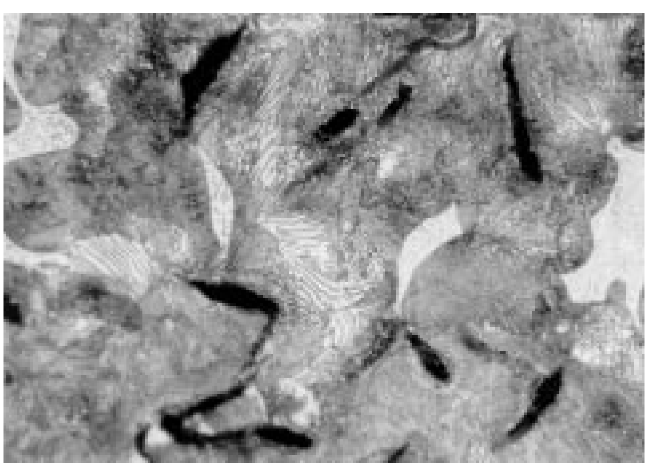

Fig. 11 Microstructure of alloy D near chill end (cast with subzero end chill). 500×

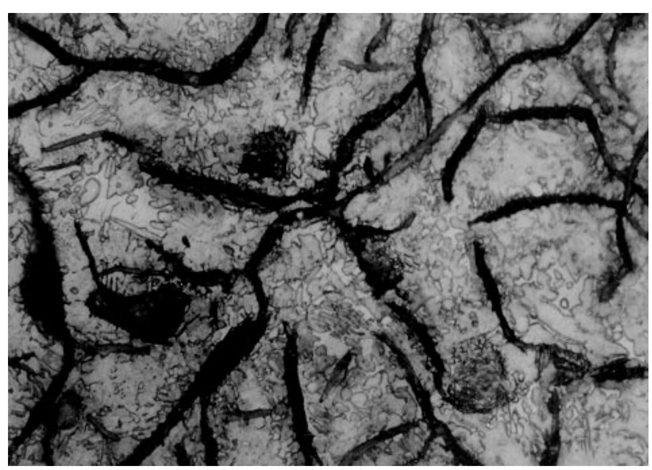

Fig. 12 Microstructure of sand cast (without chill) specimen. 500×

the eutectic as the temperature decreases through the eutectic range to the solidus. Thus, undercooling for water-cool and subzero chilled cast iron can lead to longer dendrites and higher interaction. Hence the eutectic cells solidify around these austenite dendrites, and in this manner the entire microstructure is affected by the number and size of the dendrites.

Table 4 Grain size for different alloys, measured along the length of the casting

Specimen location, distance from chill end, mm	Grains/in.^{2}			
	Alloy A	Alloy B	Alloy C	Alloy D
25	68	98	107	132
75	57	89	86	92
125	53	58	57	62
175	41	56	59	60
225	32	58	60	68

Sand casting of the same cast iron (without chill) possesses an average grain size of 34 grains/in.^{2} along the length of the casting. 100×

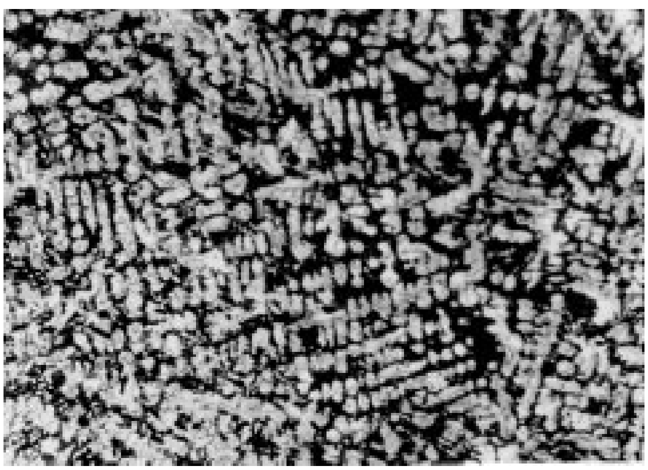

Fig. 13 Photomicrograph indicating dendrite arm spacing for alloy C (cast with water-cool chill). 500×

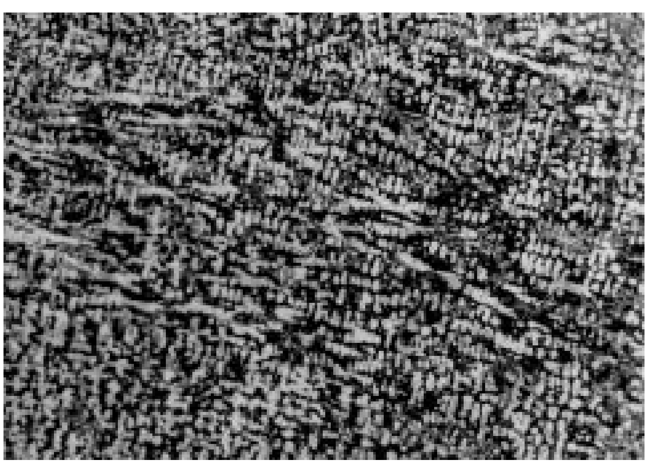

Fig. 14 Photomicrograph indicating dendrite arm spacing for alloy D (cast with subzero chill). 500×

Therefore, the general picture of solidification of chilled cast iron with various eutectic cell sizes, graphite shapes, and matrix structures can be summarized as follows: The solidification of flake graphite iron (sand cast) will start on a low number of nuclei compared to chilled (water-cool and subzero) cast iron, which is reflected by the large number of nuclei resulting in high eutectic cell count. Because the growth conditions in the liquid are favorable, these nuclei will start growing as soon as the temperature drops below the equilibrium temperature for sand cast and with maximum undercooling for chilled cast iron.

Microscopic studies reveal that the grain size of chilled cast iron (Table 4) were fine and became coarser for cast iron, cast without a chill. Thus, fine grains in chilled cast iron increases the soundness of the casting and hence the strength. It was also suggested by Read Hill (Ref 26) that strength of cast iron can be related directly to porosity level. Therefore, in the case of chilled cast iron the data indicate that dendrite morphology is the principal factor in determining the strength and not the graphite morphology.

3.2 Microstructural Examination

Primary austenite dendrite structure was observed in all the specimens tested (Fig. 13 and 14), with variations in patterns occurring as a result of differences in the rate of cooling. For each specimen the structure of the dendrites was analyzed by determining the dendrite arm spacing, the average dendrite length, the dendrite interaction, and the directionality. Marked

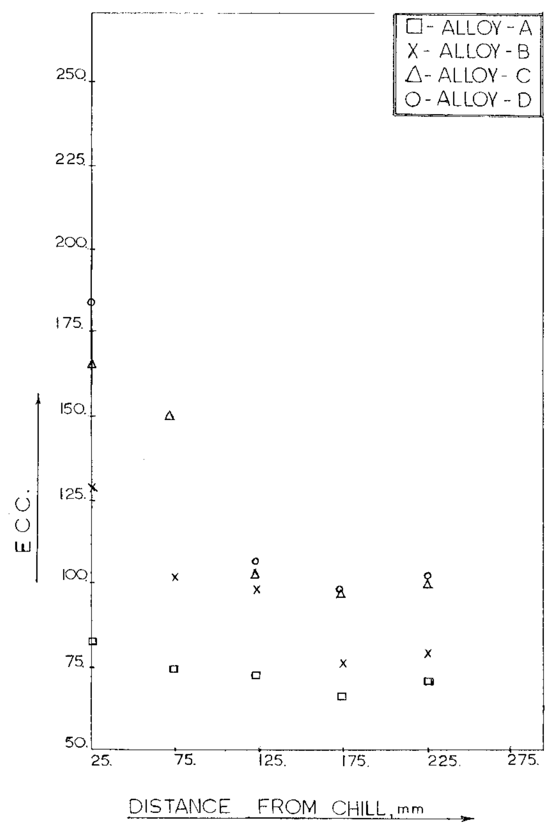

Fig. 15 Relationship between eutectic cell count and distance from chill end for different alloys

changes were also seen in the graphite morphology as the rate of cooling was varied using different types of chill. Primary austenite dendrites would be expected to develop within each of the castings produced in such a manner that their solidification is dependent on the rate of undercooling.

For the cast iron of hypoeutectic composition selected for the present investigation, because of the cooling provided during solidification, it is believed that the dendrites form prior to nucleation and growth of the eutectic. The eutectic then completes solidification by filling in the areas surrounding the dendrites. The resulting structures of transformed primary austenite dendrites traverse a number of eutectic cells, which contain both graphite and transformed eutectic austenite.

According to some investigations (Ref 27), primary austenite dendrites form in hypoeutectic gray irons only in the localized areas of carbon depletion near the primary graphite phase, which presumably solidifies first. However, in the present investigation, the observed formation of primary dendrites in the hypoeutectic iron prior to the solidification of graphite can be explained by the relatively fast cooling and the undercooling needed for graphite nucleation. This is consistent with the arguments of Ruff and Wallace (Ref 22).

Figures 8 to 12 show the microstructures of different alloys (at the chill end) chilled using various type of chills respectively (alloys A to D), in which a high concentration of cementite can be seen in the pearlite matrix. It can be seen from Fig. 15 that the ECC decreases monotonically as the distance from the chill end increases (i.e., as the rate of cooling decreases). The ECC decreases as the cooling rate decreases because there is less time available for diffusion of the solute. Hence, it is believed that diffusion controls the ECC, a deduction confirmed by other researchers (Ref 28).

3.3 Ultimate Tensile Strength

Table 2 shows the UTS of the cast iron alloys (at the chill end) chilled using various types of chills. Figure 2 is a plot showing the relationship between the UTS and the ECC for various alloys. It can be seen from Fig. 2 that UTS increases as eutectic cell count increases until the cells compact (Fig. 6). A difference can be noted between the eutectic cell count of chilled irons and cast iron cast with out chill as indicated in Fig. 3 to 7; this difference is small as compared to water cool and subzero chilled irons. Typical figures are 185 cells/cm^2 for subzero chilled iron (near chill end), 165 cells/cm^2 for water cool, chilled iron (near chill end), 128 cells/cm^2 for steel chilled iron (near chill end), and 85 cells/cm^2 for silicon carbide chilled iron (near chill end). The same cast iron cast without chill has a cell count of 72 cells/cm^2 all along the length of the casting (Table 3). It can also be seen that the UTS increases monotonically as the ECC increases, that is, moving away from the chill end toward the riser end. Tensile tests reveal that the larger dendrite interaction of undercooled irons explain why higher strengths are associated with them. Higher dendritic interaction areas reflect the interweaving of dendrites through eutectic cells that effectively tie eutectic cells together. As the ECC decreases beyond 75 cells/cm^2, however, the UTS does not seem to vary much. This indicates that for ECC below 75 cells/cm^2, the rate of cooling is slow enough that there is no supercooling effect and the UTS approaches that of fully annealed cast iron.

4. Conclusions

Analysis of data on cast irons chilled using various types of chill shows that the cooling rate has a marked effect on the ECC. The ECC was found to vary directly with the rate of cooling. The UTS however, increases as the rate of cooling increases, thus showing a direct relationship with ECC. If the rate of cooling is reduced beyond a certain point, the UTS approaches an asymptotic value, which is the UTS of fully annealed cast iron.

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