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Effect of the percentage carbon equivalent on the nodule characteristics, density and modulus of elasticity of ductile cast iron

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Successful melting and Mg treatment were conducted using a vortex unit which produced spheroidal graphite (SG) Fe ingots having a percentage carbon equivalent (%CE) ranging from 3.782 to 5.240. Microstructure examination revealed graphite nodules embedded in a white matrix (unetched condition). The variation of %CE proved to have a pronounced effect on the nodule characteristics. The nodule count showed a maximum value at %CE of 4.613. For metal-mould ingots it reached a value of 1584 nodules mm^{-2}, while for sand-mould ingots it reached a value of 970 nodules mm^{-2}. Nodule size was found to be inversely proportional to the nodule count for both sand- and metal-mould ingots. The nodularity of all ingots was, in general, higher than 95%. The density of SG Fe was found to decrease gradually (at %CE = 3.782) from 7242 to 6969 kg m^{-3}. The modulus of elasticity (E) showed a boat-like curve having minimum values of 189 and 192 GPa for the sand and metal moulds, respectively.

1. Introduction

The worldwide production of ductile Fe, or so-called spheroidal graphite (SG) Fe, has been increasing since the year 1948 up to the present [1]. Fig. 1 shows the worldwide production rates of SG Fe for the past, present and future predictions up to the year 2000. The present (1994) production is estimated to be 23 million tons per annum.

The widespread use of SG Fe is due to its advantageous properties. First, it has melting temperatures, and consequently, pouring temperatures that are 300–350 K lower than cast steel [2]. Second, because of a larger concentration of free C, SG Fe has the best fluidity and least shrinkage of any ferrous metal [2]. Third, it has better machinability when compared with cast steel. Fourth, it possesses a combination of high strength and ductility. The automotive and agricultural implement industries are the major users of SG Fe castings; with the cast iron pipe industry being another.

Although very few publications [3] report the effect of the percentage carbon equivalent (%CE) on some properties of cast Fe, to the best of our knowledge, nothing has been reported about the effect of %CE on the properties of SG Fe. Therefore, the present investigation has been devoted to study the effect of %CE on the nodule characteristics, density and modulus of elasticity of SG Fe.

2. Experimental procedure

Heats were prepared in a 90 kg, high frequency (1000 Hz) induction furnace using charges consisting of low S, low Mn and low P pig Fe (SOREL metal) and steel scrap. The chemical composition of these raw materials are listed in Table I. Desulfurization procedure was of no essential significance since the S content of raw materials was within the permissible range. The heats were heated to 1773–1823 K and transferred into a well-heated pouring ladle to the vortex unit [4]. Mg treatment and inoculation were conducted in the vortex unit when the temperature of the base Fe reached 1673 K. The ferrosilicon (FeSi) alloy containing 10 mass % Mg was used in the spheroidizing treatment. The heats were inoculated with 0.5 mass % of the charge (FeSi alloy containing 65% Si). The grain size of inoculant used ranged from 1.5 to 3 mm. Table II lists the chemical composition of all heats involved in this study. The melt was poured, at a temperature of 1623 K, into three different moulds to produce specimens for both chemical analysis and the tests; both sand and metal moulds were used. A schematic diagram of the metal mould used in the present study is shown in Fig. 2.

A standard metallographic procedure [5] was used on sectioned samples. The nodule count was performed using photographs at a magnification of 150x. The obtained values for the nodule count or nodule

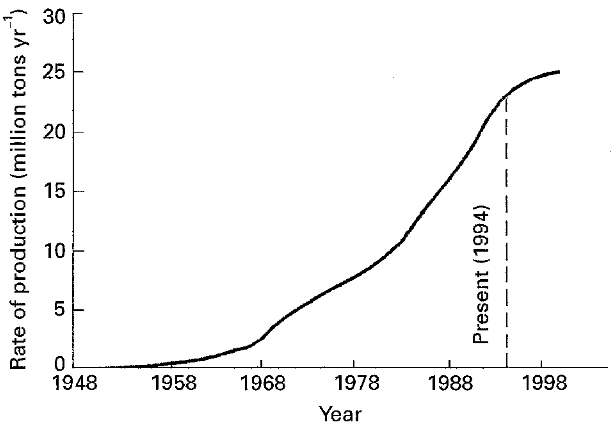

Figure 1 The worldwide production rate of SG Fe. Some values of production rate are based on industrial experts' predictions and others from the literature [1, 9].

TABLE I Chemical composition of the raw materials used in the present study

Raw materials	Composition (%)					
	C	Si	Mn	S	P	Fe
Sorel metal	4.0	0.1	0.1	0.02	0.03	bal.
Steel scrap	0.16	0.15	0.6	0.02	0.03	bal.
Ferrosilicon	0.0	65.0	0.0	0.00	0.00	bal.
Carborizer	100.0	0.0	0.0	0.00	0.00	0.0

TABLE II Chemical composition of all heats

Heat No.	Composition (mass %)					
	C	Si	Mn	P	S	Mg
1	3.255	1.681	0.13	0.02	0.01	0.05
2	3.246	2.641	0.17	0.02	0.01	0.07
3	3.494	2.057	0.16	0.02	0.01	0.03
4	3.219	3.069	0.17	0.02	0.01	0.07
5	3.122	4.583	0.17	0.02	0.01	0.07
6	3.387	5.528	0.13	0.02	0.01	0.08
7	3.392	5.935	0.17	0.03	0.01	0.08

size were, at least, the average readings for three identical specimens of each heat. The density of the SG Fe was determined using the water displacement method. The modulus of elasticity (E) values were deduced through the ultrasonic velocity by the plus-echo technique [6, 7]. The technique required the exact measurement of the time interval between two successive echoes (T), as well as the sample thickness (X). An oscilloscope (Philips PM 3055) was used to determine the time interval. The ultrasonic velocity (V) can be obtained from the relation [7]

$$V = 2X/T \quad (1)$$

and E was obtained from the relation (Ref. 7)

$$E = \frac{V^2\rho(1+\nu)(1-2\nu)}{(1-\nu)}$$

where ρ is the density (kg m^{-3}) and ν is Poisson's ratio.

Based on previous investigations [3, 11] concerning the value of Poisson's ratio it is assumed, in the present investigation, that Poisson's ratio is equal to 0.29.

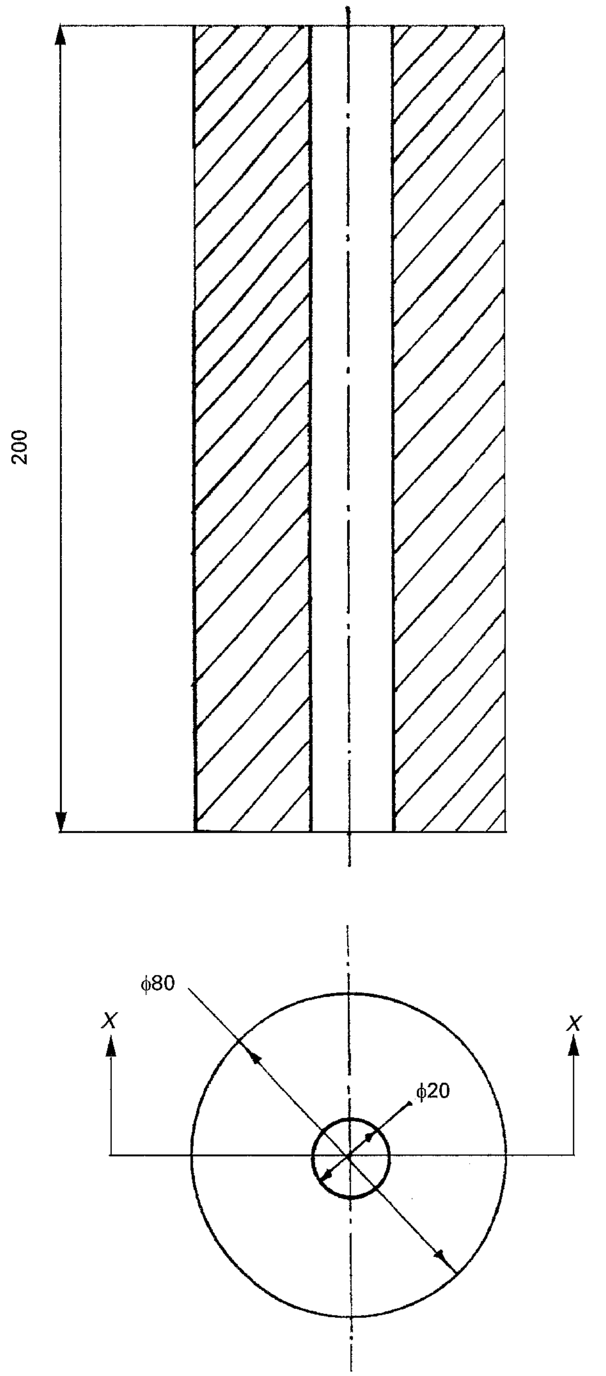

Figure 2 Schematic diagram of the metal mould used in the present investigation together with its dimensions in mm.

3. Results and discussion

3.1. Production of SG Fe having different %CE

In the present investigation, successful trials have been made to obtain SG Fe having %CE ranging from 3.782 to 5.240, for all ingots cast in sand and metal moulds. Table III lists the nominal and actual %CE of all ingots. The first four ingots were hypoeutectic while the last three were hypereutectic.

3.2. Microstructure

Fig. 3 shows the as-polished microstructures of the produced SG Fe. Fig. 3a represents the microstructures of the sand-mould ingots while Fig. 3b represents those for the metal-mould ingots; the %CE of

TABLE III Nominal and actual %CE of all heats

Description	Ingot no.						
	1	2	3	4	5	6	7
Nominal %CE	3.750	4.000	4.250	4.500	4.750	5.000	5.25
Actual %CE	3.782	4.071	4.099	4.176	4.613	5.106	5.24

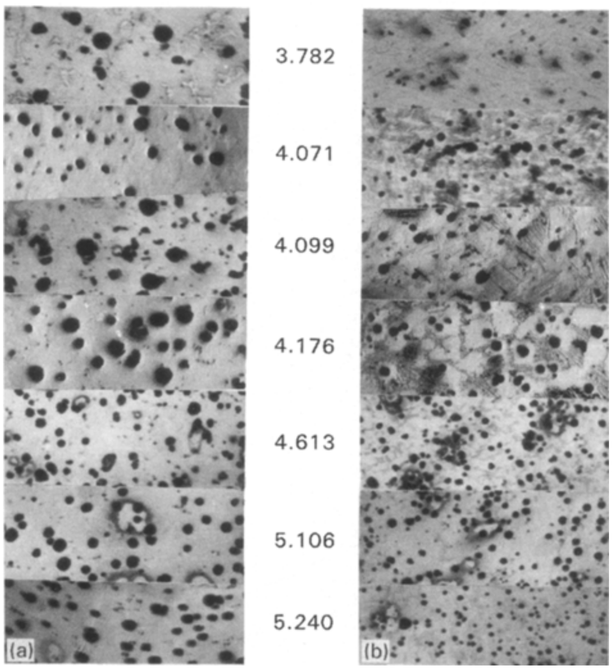

Figure 3 As-polished microstructure of SG iron with different %CE ranging from 3.782 to 5.240. (a) The sand-mould ingots; (b) the metal-mould ingots (67.5 ×).

each ingot is also given. The nodule characteristics, i.e. nodule count, nodule size and nodularity, were all detected from such photographs. Generally, the microstructure consists of spheroids (nodules) of graphite embedded in a single white matrix; the white matrix reflects the unetched condition. Details about the matrix constituents will be reported later. It can be seen from Fig. 3 that the variation of %CE does have a pronounced effect on the nodule characteristics of SG Fe.

3.3. Nodule count

Fig. 4 exhibits the variation of nodule count versus %CE of the SG Fe cast in both sand and metal moulds. Additionally, the results obtained by Pan *et al.* [8] are also reproduced in the same figure for the sake of comparison. It can be seen that the nodule count of SG Fe cast in a metal mould is, generally, higher than that cast in a sand mould [8]. The nodule count was found to increase with an increase in the cooling rate at the eutectic temperature of 1421 K [9]. Maxima in the curves of Fig. 4 can be observed at a %CE of 4.613. For each curve in Fig. 4, a slight decrease in the nodule count is noted after reaching the maximum value. For the sand-mould ingots the

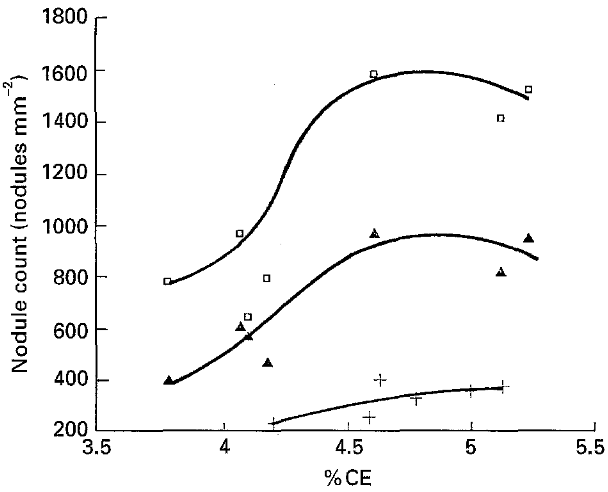

Figure 4 Variation of nodule count with %CE for SG Fe cast in sand (▲) and metal (□) moulds [Results from Ref. 8 (+) are reproduced for comparison].

nodule count ranged from 400 (at %CE = 3.782) to 970 nodules mm^{-2} (at %CE = 4.613). On the other hand, for the metal-mould ingots the nodule count ranged from 780 (at %CE = 3.782) to 1584 nodules mm^{-2} (at %CE = 4.613). The slight decrease in nodule count after the maximum may stem from C flotation occurring at this %CE [8]. Similarity between the curves obtained in the present results and those obtained previously [8] do exist. However, the latter curve shows, generally, a lower nodule count which may refer to the different chemical compositions and cooling rates in the two procedures.

3.4. Nodule size

Fig. 5 delineates the results obtained in the present investigation for the effect of %CE on the nodule size. A gradual decrease can be observed in the two curves concerning the sand- and metal-mould ingots. However, the nodule size curve for the sand-mould ingots is, generally, higher than that for the metal-mould ingots. After reaching a minimum value of nodule size at %CE of 4.613, a slight increase can be observed. For the sand-mould ingots the minimum nodule size was found to be 12 μm while that for the metal mould was 8 μm. The present trend of results confirms those obtained previously, which stated that nodule size is inversely proportional to the nodule count of SG Fe [9].

3.5. Nodularity

Fig. 6 shows the nodularity of the present SG Fe for both sand- and metal-mould ingots, together with the results obtained in Ref. 8 for the sake of comparison. [%Nodularity is defined as [10]: %nodularity = (number of nodules/number of total particles) × 100.] For the sand-mould ingots, the nodularity was almost 100% for all samples. On the other hand, a slight increase in %nodularity was observed for the metal-mould ingots reaching a value of 100% for %CE of > 4.613–5.240. Generally, even for the latter group ingots, the %nodularity was always higher than 95%.

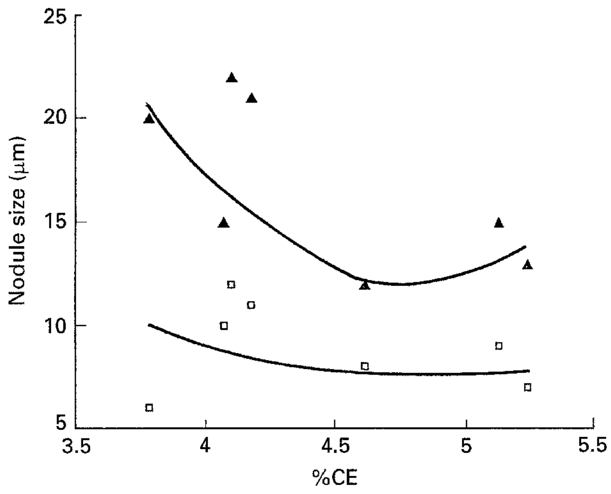

Figure 5 Variation of nodule size with %CE for SG Fe cast in sand (▲) and metal (□) moulds.

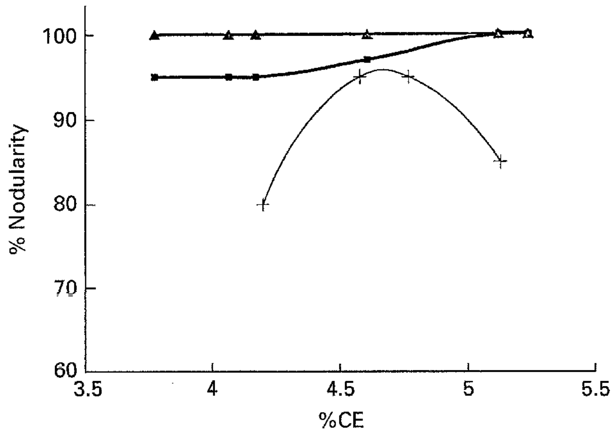

Figure 6 Variation of %nodularity with %CE for SG Fe cast in sand (▲) and metal (■) moulds [results from Ref. 8 (+) are reproduced for comparison].

Fig. 6 shows that %nodularity of the present SG Fe, cast in sand and metal moulds, are generally higher than that of Ref. 8 for all values of %CE. This may be due to the different experimental procedures of Mg treatment of SG Fe. Table IV summarizes the results obtained for the nodule characteristics for all ingots. It includes the nodule count (N), the nodule size (D) and the %nodularity at different %CE for the sand and metal moulds.

3.6. Density

Fig. 7 delineates the variation of density of SG Fe versus %CE; a slight decrease of SG Fe density with increasing %CE can be observed. The upper curve (higher density) refers to the metal-mould ingots while the lower one (lower density) refers to the sand-mould ingots. For the sand-mould ingots the largest and lowest densities were 7242 and 6969 kg m^{-3} at %CE of 3.782 and 5.240, respectively. For the metal mould ingots, the largest and lowest densities were found to be 7623 and 7042 kg m^{-3}. These results are comparable to those reported previously [11]. A low C pearlitic SG Fe showed a density of 7400 kg m^{-3}. For a high C ferritic SG Fe, a density as low as 6800 kg m^{-3} was reported [11].

TABLE IV Effect of %CE on nodule count, nodule size and nodularity of all ingots

Ingot no.	%CE	N (nodules mm^{-2})	D[a] (μm)	%Nodularity
1-S	3.782	400	20.0	100
2-S	4.071	610	15.0	100
3-S	4.099	575	22.0	88
4-S	4.176	472	21.0	100
5-S	4.613	970	12.0	100
6-S	5.106	817	15.0	100
7-S	5.240	925	13.0	100
1-M	3.782	780	6.0	95
2-M	4.071	969	10.0	95
3-M	4.099	646	12.0	78
4-M	4.176	792	11.0	95
5-M	4.613	1584	8.0	100
6-M	5.106	1415	9.0	99
7-M	5.240	1524	7.0	99

[a] Nodule diameter.

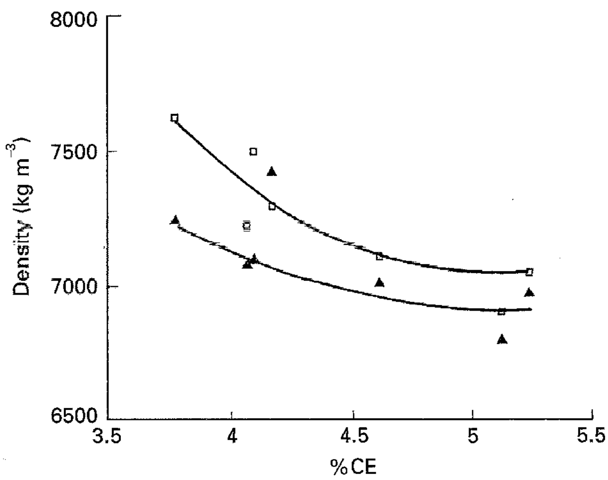

Figure 7 Variation of density with %CE of SG Fe cast in sand (▲) and metal (□) moulds.

3.7. Modulus of elasticity (E)

The variation of E versus %CE of SG Fe is shown in Fig. 8. The curve representing E for the metal-mould ingots is higher than that for the sand-mould ingots. Boat-like curves, shown in Fig. 8, illustrate minima in the E values at %CE of 4.613. Many factors were reported to affect the E value of cast Fe [3]: (1) graphite content; (2) form of graphite; (3) P content; (4) type of matrix; and (5) the melting temperature of the iron [3, 12]. In the present study, the total C content in the different heats was more or less constant (falls within a narrow range), therefore, the C content parameter is minor. Nodularity was always higher than 95% which reflects the fact that the graphite form was always nodular and this parameter can, thus, be excluded. The P content and the matrix structure have little effect on E [3]. It is now logical to assume that the form of the curves in Fig. 8 was related to the melting temperatures of the different ingots with %CE ranging from 3.782 to 5.240. Table V summarizes the results obtained for the density and E for ingots cast in sand and metal moulds. Further studies are needed in

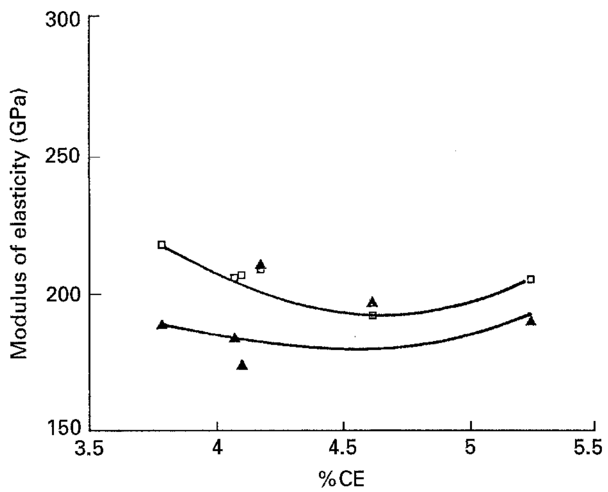

Figure 8 Variation of E with %CE of SG Fe cast in sand (▲) and metal (□) moulds.

TABLE V Effect of %CE on density and E of SG Fe cast in both sand and metal moulds

Ingot no.	%CE	Density ($kg\,m^{-3}$)	E (GPa)
1-S	3.782	7242	189
2-S	4.071	7080	184
3-S	4.099	7099	174
4-S	4.176	7422	211
5-S	4.613	7010	197
6-S	5.106	6795	289
7-S	5.240	6969	190
1-M	3.782	7623	218
2-M	4.071	7220	206
3-M	4.099	7495	207
4-M	4.176	7291	209
5-M	4.613	7104	192
6-M	5.106	6897	270
7-M	5.240	7042	205

this area in order to confirm and enlighten the present results.

4. Conclusions

1. Successful trials were achieved to cast SG Fe, in sand and metal moulds, having %CE ranging from 3.782 to 5.240.

2. The curves representing the variation of nodule count versus %CE showed maxima at %CE of 4.613. For the sand-mould ingots, this maximum was 970 nodules mm^{-2}. A maximum of 1584 nodules mm^{-2} was observed for the metal-mould ingots.

3. Nodule size was found to be inversely proportional to the nodule count of SG Fe. Minima in the curves of the variation of nodule size versus %CE were 12 and 8 μm at %CE of 4.613 for the sand- and metal-mould ingots, respectively.

4. For the sand-mould ingots it was found that the nodularity was almost 100% for all samples. The nodularity for the metal-mould ingots increased from 95% at low %CE to 100% for all samples having %CE $\geqslant$ 4.613.

5. A gradual decrease in the density of SG Fe was found to occur on increasing of %CE from 3.782 to 5.240. A decrease from 7242 to 6969 $kg\,m^{-3}$ was observed for the sand-mould ingots, while for the metal-mould ingots it was 7623–7042 $kg\,m^{-3}$.

6. The variation of E of SG Fe versus the %CE showed a boat-like curve. Minima in the E values were observed for both sand- and metal-mould ingots. The minima in these curves were 189 and 192 GPa, respectively. The metal-mould ingot's curve was, generally, higher than that of sand-mould ingot's, curve.

References

1. S. KARSAY, "Ductile Iron: State of the Art" (Qit-Fer et Titane, Canada, 1982).
2. W. BRADLEY and M. SRINIVASAN, *Int. Mater. Rev.* **35** (1990) 63.
3. H. ANGUS, "Cast Iron Physical and Engineering Properties" 2nd Edn (British Cast Iron Research Association, London, 1978).
4. H. BAKKERUS and B. V. HOLEST, *Modern Casting* **March** (1981) 41.
5. ASM, "Metals Handbook: Casting", Vol. 15 (Metals Park, OH, 1992).
6. S. AVNER, "Introduction to Physical Metallurgy" (McGraw Hill, Tokyo, 1974) p. 450.
7. T. HUETER and R. BOTT, "Sonic Techniques for the Use of Sound and Ultrasonic in Engineering Science" (Wiley, New York, 1965).
8. E. PAN, W. HSU and C. LOPER, *AFS Trans.* **96** (1988) 654.
9. S. KARSAY, "Ductile Iron: The Production Practices" (American Foundrymen's Society for Metals, USA, 1979).
10. C. WHITE, R. FLINN and P. TROJAN, *AFS Trans.* **89** (1981) 639.
11. ASM, "Metals Handbook: Properties and Selection", Vol. 1 (American Society for Metals, OH, 1978).
12. N. FATAHALLA, "A Treatise on Mechanical Metallurgy" (Al Ahram, Galaa Street, Cairo, Egypt, 1993).

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