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Metallurgical parameters, mechanical properties and machinability of ductile cast iron

N. FATAHALLA, S. BAHI
Department of Mechanics, Faculty of Engineering, Al Azhar University, Cairo, Egypt
O. HUSSEIN
The Information Center, El Nasr Castings Co., Giza, Egypt

Results on the effect of solidification cooling rate on the microstructure, mechanical properties and machinability of spheroidal graphite (SG) iron have been presented. The effect of ferritic heat treatment on the same properties has been also investigated. The microstructural observation, tensile properties and hardness values of the present SG iron has been developed. The tool life criterion was used as a measure of machinability. It was found that during turning of SG iron by using a single point cutting tool, its life increased with decreasing the solidification cooling rate for both sand and metal moulds. The tool life was found to be significantly affected by the variation of nodule characteristics. A decrease in tool life due to an increase of nodule count was observed. The tool life was found to be directly proportional to the ductility of SG iron whether for the as cast or ferritic heat-treated ingots.

1. Introduction

Cast iron has a long and illustrious history and the five types of cast iron produced commercially today are; (i) white, (ii) grey, (iii) malleable, (iv) spheroidal graphite (SG) or ductile, and (v) compacted. The development in the late 1940s, after the Second World War, of an iron that was ductile as cast ought to have revolutionized the concept of cast iron [1, 2]. SG iron has been used to replace cast steel because of its many advantageous properties such as: higher strength-to-weight ratio, higher toughness, damping capacity, better wear resistance, better fluidity, lower melting point, better hot-workability and hardenability [1, 3–6]. The low cost of production, very good castability, good machinability, and shorter heat-treatment processing cycles are additional merits of SG iron. Consequently, the SG iron castings have been utilized in many structural applications [1, 3].

The histogram of Fig. 1 illustrates the evolution of the worldwide production of the SG iron from 1948 until the year 2000. Owing to its attractive characteristics, the annual worldwide production of SG iron has been increasing and it reached a value of about 24 million tonnes through the year 1993. It is expected to reach its steady state condition in the near future and until the year 2000 with a rate of about 25 million tonnes per annum.

Up to the year 1990 few studies had been carried out relating metallurgical parameters and mechanical properties to machinability of cast iron. J. Berry *et al.* [7] indicated that most published data had been focused on grey cast iron. Therefore, the present investigation was devoted to enlighten the relation between metallurgical parameters, mechanical properties and machinability of SG iron.

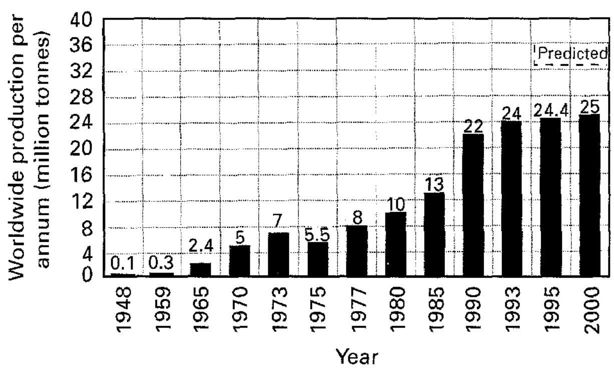

Figure 1 Worldwide production of SG iron from year 1948 to 2000.

2. Experimental procedures

2.1. Materials, chemical analysis and melting practice

Eighty precent of the charge was pig-iron with 3.9% C and 0.9% Si. The remaining 20% was return SG iron with 3.6% C, 2.4% Si and 0.05% Mg. The materials were melted in a basic high frequency induction furnace. The liquid metal was treated by Fe–Si–Mg alloy (45, 50 and 5 mass % respectively, 1.6% by weight of charge) having a grain size from 15 to 50 mm using the ladle-sandwich technique [8]. The melt was then inoculated (0.6% by weight of charge), using Fe–Si alloy (20 and 80% by weight, respectively),

TABLE I Summary of the temperatures of iron through different stages up to its casting

Operation	Temperature K	(°C)	Duration (min)
Superheating of the melt	1773	(1500)	5
After pouring into the ladle	1739	(1466)	2
Transfer to treatment location			5
Mg-treatment (a) Before	1678	(1405)	
(b) After	1623	(1350)	4
Transfer to casting location			1
Pouring process (a) Sand mould	1598	(1325)	2
(b) Metal mould	1578	(1305)	1

TABLE II Chemical analysis of the molten metal used in the present study

Element Condition	C (%)	Si (%)	S (%)	Mn (%)	P (%)	Al (%)	Mg (%)	CE (%)
Before Treatment	3.80	1.20	0.016	0.13	0.03	0.005	0.002	4.19
After Treatment	3.54	2.60	0.011	0.14	0.03	0.010	0.058	4.35

having a grain size from 0.2 to 3 mm. Table I summarizes the temperatures of iron through different stages. Spectrograph samples were cast into copper moulds for analysis in a spectrograph. The chemical analysis of the present SG iron heats before and after Mg-treatment is given in Table II. The %CE was calculated using the following equation [9]

$$\%CE = \%C + 0.33P + 0.45\%S - 0.02Mn$$

The %CE is also included in Table II.

2.2. Casting

In the sand casting procedure the ingots were cast vertically producing 16 cylindrical ingots from each heat as can be seen in Fig. 2. The ingot diameters being; 25, 45, 65 and 85 mm with a common height of 300 mm. On the other hand, ingots were cast into individual metal mould producing ingots with diameters of 15, 20, 25 and 45 mm with a common height of 200 mm. This variety of diameters in both sand and metal moulds aimed at covering a wide range of solidification cooling rates. The casting temperatures and duration are also given in Table I.

2.3. Ferritic heat treatment

The ferritic treatment was performed using a Gallenhamb muffle furnace with maximum temperature of 1373 K and accuracy of ± 5 K. The temperature–time relationship during the ferritic treatment of the present SG iron is illustrated schematically in Fig. 3.

2.4. Metallographic procedure

Standard metallographic techniques [10–13] were used. Microstructural observations implied the nodule characteristics on polished samples and matrix characteristics on etched samples.

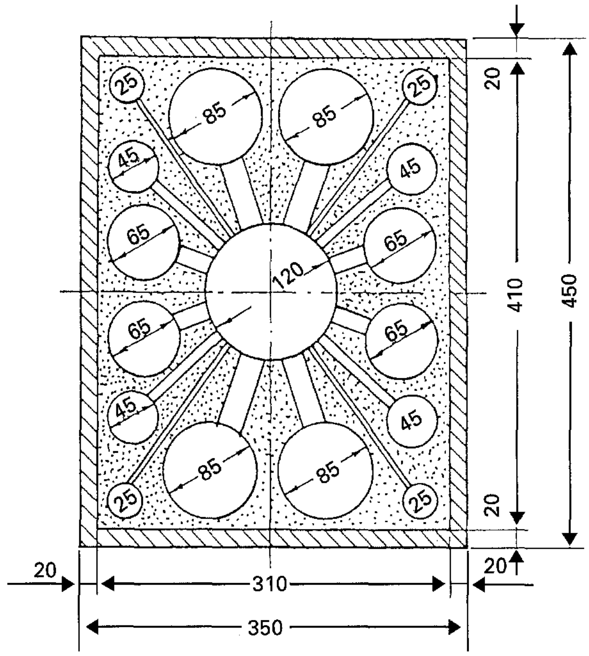

Figure 2 Sectional plan in the sand-mould showing the distribution of cavities for simultaneous casting with different diameters. (Dimension in mm)

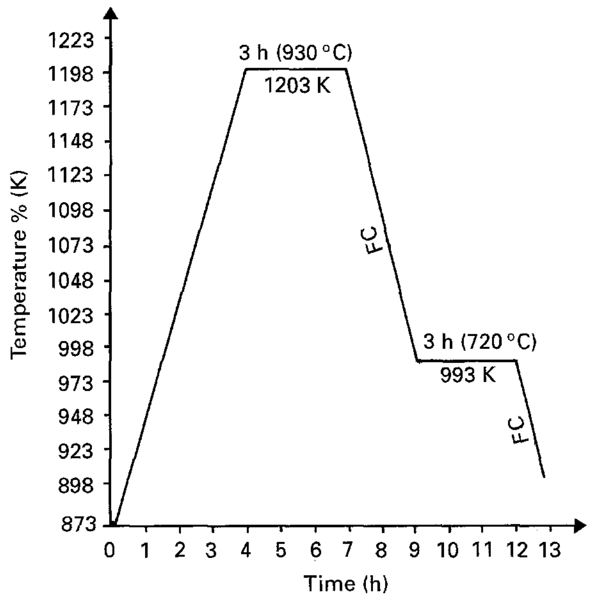

Figure 3 Temperature–time relationship through the ferritic heat treatment used in the present study.

2.5. Hardness tests

Hardness measurements were carried out using three indentation hardness tests, namely: (i) Brinell, (ii) Rockwell and (iii) Vickers'. Standard techniques [11] were used.

2.6. Tensile tests

Tensile properties were obtained from standard test specimens which were machined to gauge diameter of

5 mm and gauge length of 25 mm. A motor driven tensiometer machine (type W) was used. The tests were carried out at room temperature (300 K) and at a strain rate of 0.0004 per second.

2.7. Machinability tests

The flank-wear of a single point HSS cutting tool being measured during cutting the specimens on a lathe was taken as a judge for machinability. The tests were always performed without lubrication. The cutting speed, feed and depth of cut used in the present investigation were carefully selected according to a survey for the recommended cutting conditions for grey cast iron [14], steels [15] and SG iron [16]. Comparable hardness values for the present alloys and those in the literature were always taken into consideration. The cutting speed was chosen to be $30\,\mathrm{m\,min^{-1}}$, the feed 0.1 mm per revolution and the depth of cut was 1 mm. A universal measuring microscope, Zeiss model 10366, was used to measure the wear area on the flank of the tool. Measurements of the flank were made at suitable intervals of machining.

3. Results and discussion

3.1. Microstructural features

Fig. 4(a, b) show the microstructures of SG iron ingots which were cast in sand mould. The left hand group of photos show, at increasing ingot diameters (starting from the upper side), the as polished microstructure. The increase of graphite nodule diameter and the decrease of number of nodules per mm^2 are observed to be characteristic features with increasing the ingot diameter. The right hand group of photos show the etched microstructure of the sand mould ingots. While the bull's eye structure surrounded by pearlite can be observed in Fig. 4 (b-1, 2); photo (b-4) reveals an almost ferritic matrix which reflects the effect of slower solidification cooling rate on microstructure.

Fig. 5(a, b) show the microstructure of the metal mould ingots in the polished (a) and etched (b) conditions. An explanation similar to that given in the above paragraph can be given here. However, generally speaking the graphite nodule size is smaller and the nodule count is higher in the latter case. A large amount of cementite in the matrix can be observed in Fig. 5(b) specially for small ingot diameters (cf. Fig. 5(b-1)).

There was no effect of ferritic heat treatment on any of the nodule characteristics neither for sand nor metal-mould ingots. However, all ingots showed ferritic matrix after heat treatment.

Table III summarizes the results of the nodule characteristics for both sand and metal-mould ingots. The nodule count ranged from 233 nodules mm^{-2} (for the largest sand mould ingot of 85 mm) to 1638 nodules mm^{-2} (for the smallest metal mould ingot of 15 mm). The nodule size ranged from 50 μm to 5 μm for the same ingots mentioned above, respectively. These results are in good agreement with those in the literature [1, 6, 17–20]. Nodularity has been defined [21] as

$$\%\text{Nodularity} = (\text{Number of nodules}/\text{Total number of graphite particles}) \times 100$$

In the present investigation, nodularity was found to be > 95% and > 90% for the sand and metal mould ingots, respectively, as can be seen in Table III.

3.2. Hardness property

Table IV summarizes the variation of H_V with the ingot diameter for the SG iron cast in both sand and metal moulds. Generally speaking, a monotonic decrease in hardness values can be observed with increasing of the ingot diameter. It is also interesting to indicate the variation of H_V with the ingot diameter for the heat-treated ingots. These ingots showed completely ferritic matrix. Therefore, the variation of hardness refers mainly to the variation of the nodule characteristics. A hardness conversion table is given in Table V for the SG iron of the present investigation.

3.3 Tensile properties

Table VI summarizes the tensile properties of the SG iron ingots cast in both sand and metal moulds. Generally, an increase in the ductility and a decrease in proof stress and ultimate strength can be observed with increasing the ingot diameter. The ferritic heat treatment has generally increased the ductility and decreased the strength in comparison with the as cast alloys. The present results are in good agreement with those in the literature [1, 3, 5, 6, 16, 17, 19, 22].

3.4. Machinability

The variation of the flank wear with the machining time for the sand-mould ingots is shown in Fig. 6. The increase in the ingot diameter resulted in an increase of the machining time. It is to be mentioned here that the cutting tool was resharpened when its wear reached a value of 0.7 mm. The form of curves shown in Fig. 6 corresponds well with that given in the literature [23]. The rate of change of stage II (steady state region) in these curves show an increase with the decrease in diameter. The ferritic heat treatment of the sand- and metal-mould ingots resulted in a significant improvement in the machining time (tool life) of the cutting tool as can be seen in Fig. 7(a, b). A similar explanation to that given above can be given also for these curves. Since the very hard as cast metal-mould ingots were found to be suitably machined with special cutting tools (other than HSS) therefore, it was set aside for future study. The ferritic heat treatment of the metal-mould ingots revealed moderate machining time in comparison with that for the sand-mould ingots. Table VII summarizes the measured machining times (tool lives) for the different SG iron ingots investigated in the present research.

In order to delineate the effect of metallurgical parameters and mechanical properties on the

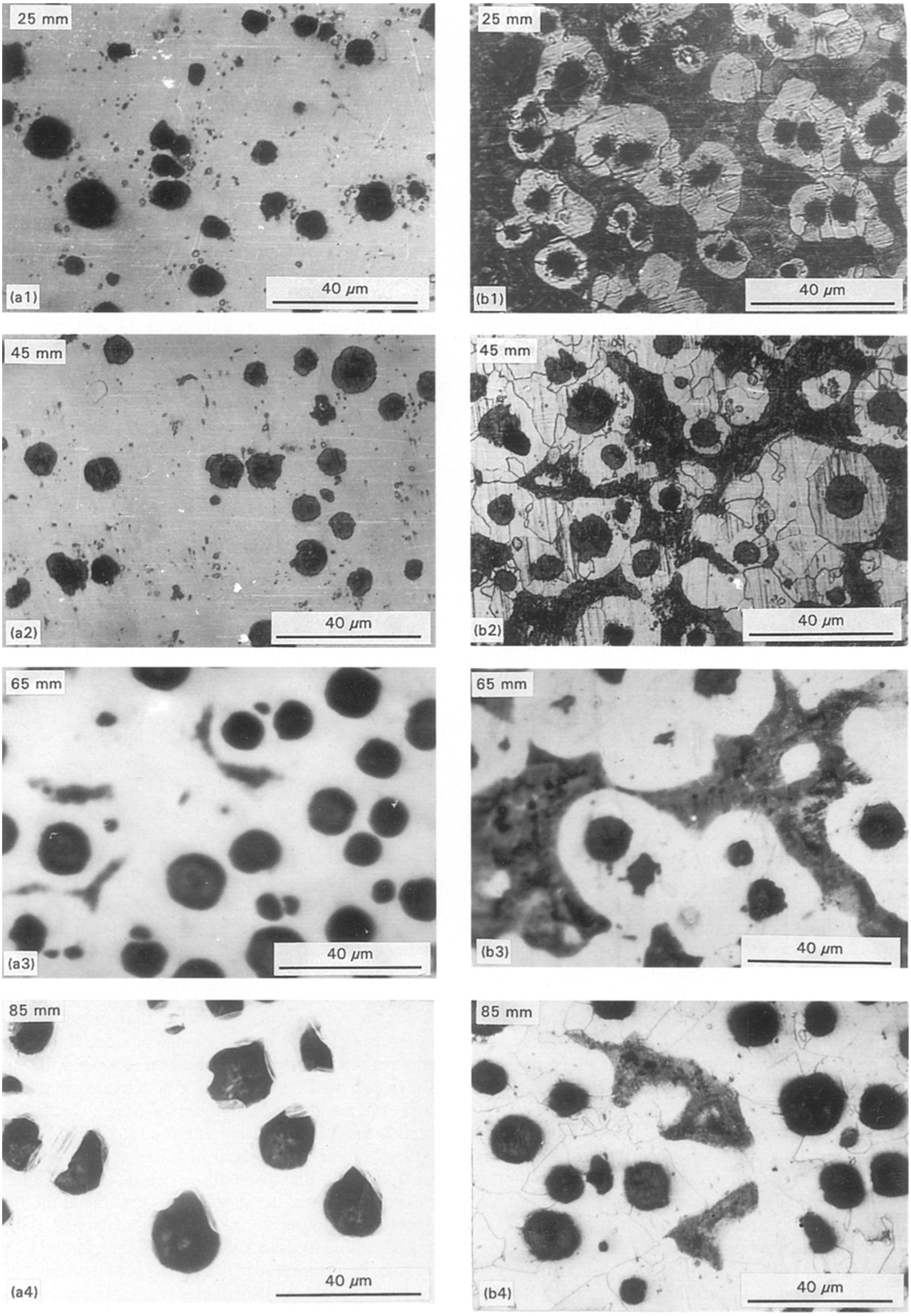

Figure 4 The microstructure of the SG iron cast in sand-mould, (a) as polished and (b) etched with Nital solution. The number on the left of photos refers to the ingot diameter.

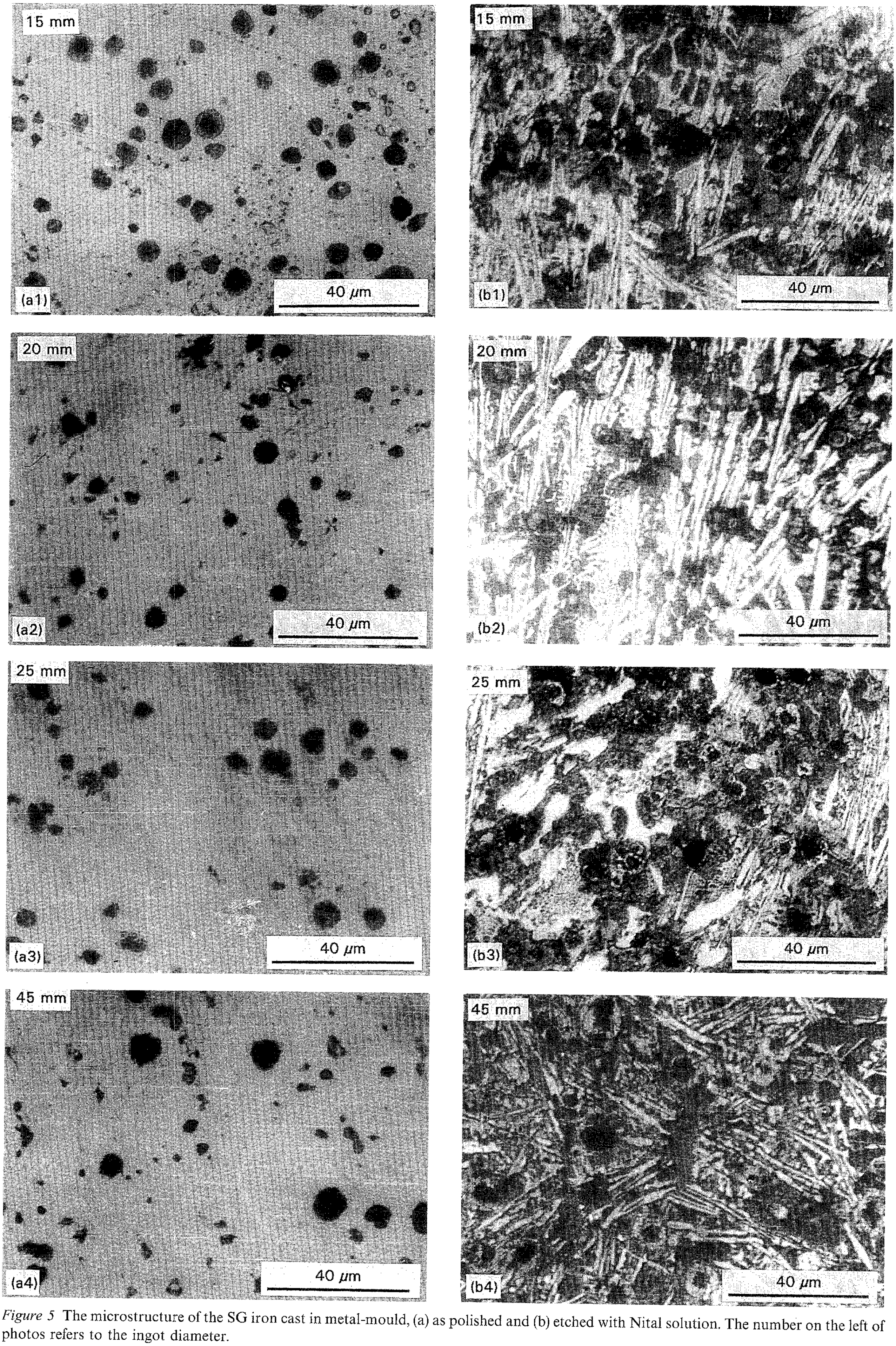

Figure 5 The microstructure of the SG iron cast in metal-mould, (a) as polished and (b) etched with Nital solution. The number on the left of photos refers to the ingot diameter.

TABLE III The nodule characteristics for the sand- and metal-mould ingots

Ingot diameter (mm)	Sand-Mould			Ingot diameter (mm)	Metal-Mould		
	Nodules (mm^2)	Size (μm)	Nodularity (%)		Nodules (mm^2)	Size (μm)	Nodularity (%)
25	1070	10	100	15	1638	5.0	99
45	972	12	95	20	1226	5.6	90
65	300	40	97	25	1128	6.4	99
85	233	50	99	45	1098	10.7	90

Nodule characteristics were the same for the ingots cast and as-heat treated.

TABLE IV The average Vickers hardness for the ingots cast in sand- and metal-mould

Sand-Mould			Metal-Mould		
Ingot diameter (mm)	As-cast H_V (MPa)	As-heat treated H_V (MPa)	Ingot diameter (mm)	As-cast H_V (MPa)	As-heat treated H_V (MPa)
25	2450	1760	15	6810	1780
45	2110	1600	20	5140	1720
65	1810	1540	25	4280	1670
85	1700	1500	45	3950	1570

TABLE V The conversion table for hardness of the SG iron produced in the present study

Ingot	H_V (MPa)	HB (MPa)	HRB	HRC
M1c	6810	6120		57
M2c	5140	4660		48
M3c	4280	4160		44
M4c	3950	3500		40
S1c	2450	1970	97	
S2c	2110	1690	91	
S3c	1810	1620	87	
S4c	1700	1590	85	
M1t	1790	1710	89	
M2t	1720	1650	87	
M3t	1670	1610	86	
M4t	1570	1490	83	
S1t	1780	1650	88	
S2t	1600	1540	84	
S3t	1540	1510	83	
S4t	1500	1480	81	

machinability (tool life) of SG iron, the curves shown in Fig. 8 were plotted. The left hand column (a) depicts the variation of the tool life with the H_V for the as cast and heat-treated ingots. A logical decrease in tool life was observed with the increase of H_V for the as cast ingots. However, it is interesting to note that for the heat-treated (whether sand- or metal-mould) ingots while the hardness is more or less constant, the tool life has remarkably changed. These latter results reflect the important role played by the nodule characteristics on the tool life since the matrix in these cases was always completely ferritic. The central column (b) shows the variation of the tool life with the nodule count. The bottom curve shows the decrease of tool life with increasing the nodule-count which is concomitant to the formation of pearlite or cementite in the matrix. However, the variation of tool life with the nodule count in the upper two curves reflects the sole effect of nodule characteristics. Finally, the variation of the tool life with the increase of ductility is depicted

TABLE VI The tensile properties for the ingots cast in sand- and metal-mould

Sand-mould							Metal-mould						
Ingot diameter (mm)	As-cast			As-heat treated			Ingot Diameter (mm)	As-cast			As-heat treated		
	σ Pr. (MPa)	UTS. (MPa)	P. (%)	σ Pr. (MPa)	UTS. (MPa)	P. (%)		σ Pr. (MPa)	UTS. (MPa)	P. (%)	σ Pr. (MPa)	UTS. (MPa)	P. (%)
25	398	525	2.4	340	446	6.4	15	630	645	0.5	326	408	2.5
45	367	485	7.25	308	426	11.0	20	615	635	0.8	316	391	3.4
65	316	444	8.00	299	423	16.0	25	582	615	1.2	298	384	4.0
85	303	418	14.0	293	415	18.75	45	530	579	2.0	283	363	6.5

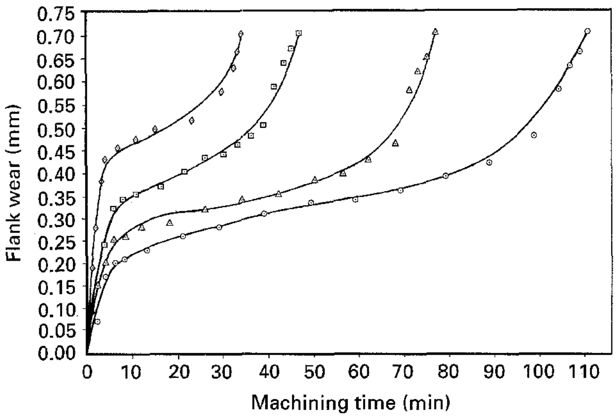

Figure 6 Flank wear of HSS tool versus the machining time for the ingots cast in sand-mould. Cutting speed 30 m min^{-1}, feed 0.1 mm per revolution, depth of cut 1 mm. ◊ S1c; ⊡ S2c; △ S3c; ⊙ S4c.

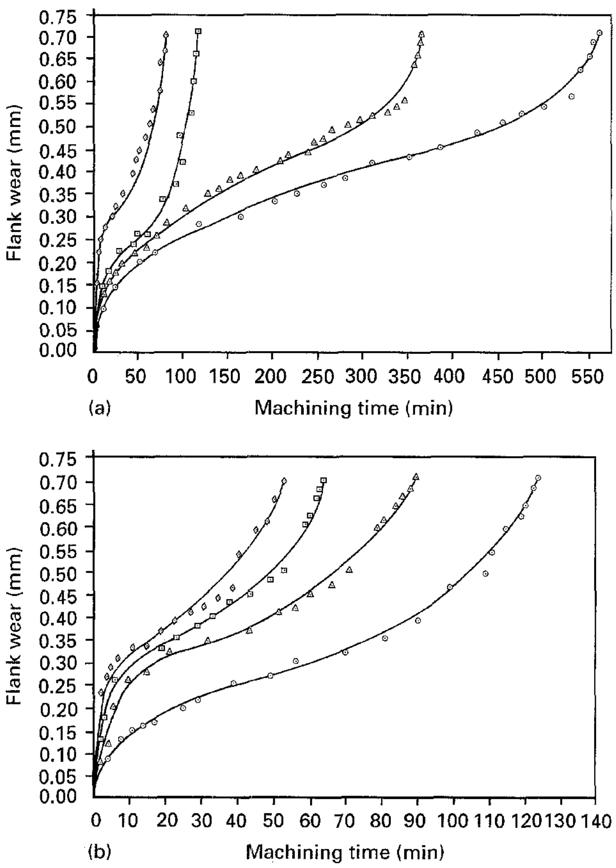

Figure 7(a) Flank wear of HSS tool versus the machining time for the ingots cast in sand-mould and heat treated. Cutting speed 30 m min^{-1}, feed 0.1 mm per revolution, depth of cut 1 mm. ◊ S1t; ⊡ S2c; △ S3c; ⊙ S4t. (b) Flank wear of HSS tool versus the machining time for the ingots cast in metal-mould and heat treated. Cutting speed 30 m min^{-1}, feed 0.1 mm per revolution, depth of cut 1 mm. ◊ M1t; ⊡ M2t; △ M3t; ⊙ M4t.

in the right hand group of curves (c). The bottom curves delineates the increase of tool life with the increase in ductility. This improvement in the tool life reflects the formation of higher percent of ferrite in the matrix (with higher ductility) and additionally, the effect of nodule characteristics. After heat treatment the matrix in all ingots was transformed into ferritic matrix and the only parameter controlling the properties was then the nodule characteristics. The central

TABLE VII The tool life in minutes of the ingots cast in the sand- and metal-moulds

Ingot	Sand-mould		Ingot	Metal-mould
	As-cast	As-heat treated		As-heat treated
S1 (25 mm)	34	81	M1 (15)	53
S2 (45 mm)	47	116	M2 (20)	64
S3 (65 mm)	77	364	M3 (25)	90
S4 (85 mm)	111	560	M4 (45)	124

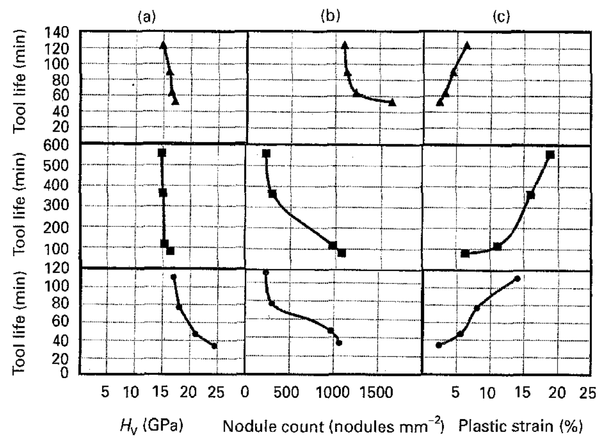

Figure 8 The tool life versus (a) hardness, (b) nodule count and (c) plastic strain for the ingots cast in sand and metal moulds.

and upper curves of (c) in Fig. 8 showed the improvement of tool life with the increase of ductility in the absence of any matrix effect. Again, the nodule characteristics have proved to be significant parameters controlling the SG iron properties.

4. Conclusions

1. The solidification cooling rate was found to, significantly, affect the nodule characteristics. The nodule count ranged from 233 to 1638 nodules mm^{-2} for the largest diameter in sand mould ingots and smallest diameter in the metal-mould ingots respectively. Additionally, the nodule size ranged from 50 to 5 μm respectively. Nodularity was found to be > 90% for all ingots.
2. The relative amounts of the matrix constituents being: ferrite, pearlite and cementite were directly related to the solidification cooling rate.
3. The Vickers hardness was found to decrease with the increase of ingot diameters. For the metal-mould ingots it ranged from 6810 to 1570 MPa, and for the sand-mould ingots it ranged from 2450 to 1700 MPa. A hardness conversion table was detected for the SG iron used.
4. A monotonic increase in ductility and decrease in strength was observed to occur with the increase in the ingot diameter. The ferritic heat treatment

resulted generally in an increase of ductility and decrease of strength for both sand- and metal-mould ingots in comparison with the as cast ingots.

5. Through machining of SG iron on a lathe, the single edge cutting tool life increased with increasing the ingot diameter for both sand metal moulds.
6. For the heat treated ingots although the hardness values are almost constant, the tool life has remarkably changed due to the variation of the nodule characteristics.
7. For the heat-treated ingots the decrease in tool life due to the increase of nodule count reflects the important effect of nodule characteristics on the machinability of SG iron.
8. For the heat-treated ingots the improvement in the tool life with the increase in ductility values emphasizes the role played by the mechanical properties on the machinability of SG iron.

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