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Swain, Mishra and Sen

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Influence of processing variables on the mechanical behavior of spheroidal graphite cast iron

1 **Susanta K. Swain** PhD
Department of Metallurgical & Materials Engineering, National Institute of Technology, Rourkela, Odisha, India

2 **Subash C. Mishra** PhD
Department of Metallurgical & Materials Engineering, National Institute of Technology, Rourkela, Odisha, India

3 **Sudipta Sen** PhD
Department of Metallurgical & Materials Engineering, National Institute of Technology, Rourkela, Odisha, India


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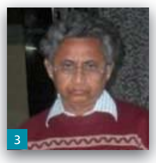
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The mechanical properties achievable from spheroidal iron castings are adequate for a very wide range of applications. Apart from mechanical properties, a number of other characteristics such as density, thermal expansion, thermal conductivity, specific heat, electrical conductivity, magnetic properties, and acoustic properties are also of considerable importance. Efforts are being made to improve all these properties. In the present investigation, five melts of SGI castings (M1 to M5) were prepared by standard foundry procedure and practices. The mechanical behavior of spheroidal graphite iron (SGI) castings was studied as a function of processing variables. It is found that the mechanical properties (viz. Tensile strength, Yield strength, Elongation, Impact resistance, etc) for a given chemical composition are highly dependent on processing variables (i.e. pouring temperature, preconditioning of base iron, inoculation practice, and molding materials). SGI castings are produced and tested as per ASTM 395 specifications. From the results, it is found that with varying processing conditions, the mechanical properties have been improved to a great extent; that is, the UTS (Ultimate Tensile Strength), YS (Yield Strength), EL(Elongation), and impact strength (at −20°C). The UTS has improved to 475·41 MPa; YS is also enhanced to 316·94 MPa; elongation has increased to 18%, but there is reduction in impact strength.

1. Introduction

It was declared at the 1948 AFS castings congress that small additions of certain elements resulted in the formation of spheroidal graphite in as-cast iron. This lead to the birth of a new engineering material namely SG iron. Independent studies at the British Cast Iron Research Association using cerium additions and in the United States at the International Nickel Company using magnesium additions demonstrated the dramatic effect of these elements on promoting the formation of a spheroidal, rather than flake graphite morphology developed during solidification. It is the key factor responsible for the unique mechanical and physical properties of ductile iron (Lacaze *et al*., 1998). The use of ductile iron has been increasing constantly since its introduction in the market in the 1950s, due to its excellent mechanical properties and low production costs (Dommarco *et al*., 2006; Schrems *et al*., 2003).

Ductile iron is defined as a high carbon-containing iron-based alloy in which the graphite is present in compact, spherical shapes rather than in the shape of flakes. Its chemical composition and carbon content is almost the same as grey iron. The transformation to ductile iron occurs when molten grey iron is treated with magnesium. The insertion of magnesium into the pouring ladle transforms the graphite flakes into spheroids. These spheroids strengthen the metal by acting as crack arresters instead of crack assistors (Ductile Iron Pipe Research Association, 2005). As far as properties are concerned, it is easy to cast, exhibits better strength and ductility and excellent corrosion resistance, good machinability and low cost per unit strength (Ductile Iron Pipe Research Association, 2005; Dommarco *et al*., 2004). The microstructure of commercial SG irons in as-cast state or after heat treatment consists pearlite and graphite nodules (Figures 1–5) embedded in a ferrite shell. This is the so-called *bull's eye structure* (Lacaze *et al*., 1997). The control of this microstructure is of practical importance because it determines the mechanical properties of SG irons. Reducing the weight of ductile iron castings is an important method for saving energy and materials. For example, in case of an automobile, a reduction of 100 kg in weight saves 0·5 liter of petrol for 100 km distance (Dommarco *et al*., 2006). So, many metallurgical researchers are dedicating themselves for developing and perfecting thin-section ductile iron casting technology (Choi *et al*., 2004).

Considering the development of mechanical properties of SGI castings in as-cast condition, the present efforts have been focused on control of processing variables in different stages during tapping

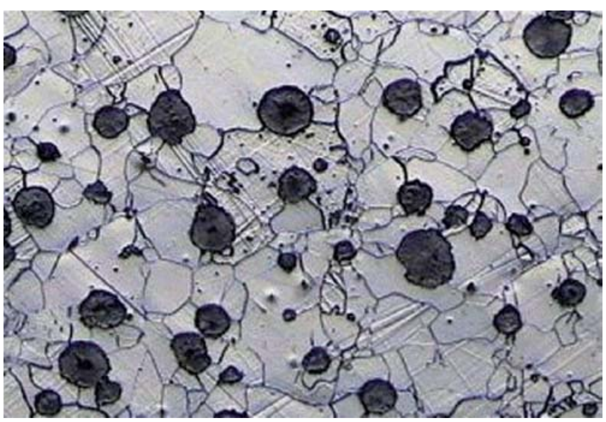

Figure 1. Microstructure of melt M1 (100×, 80% nodularity).

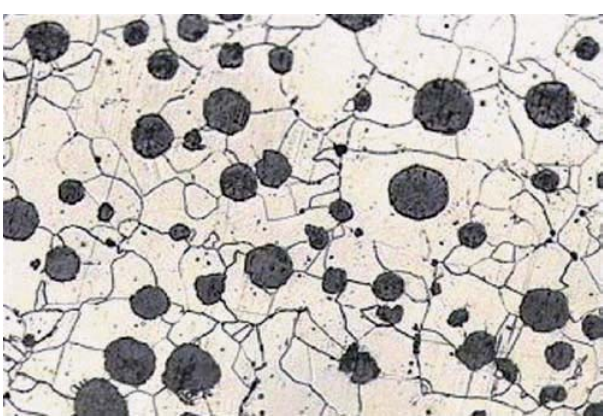

Figure 2. Microstructure of melt M4 (100×, 90% nodularity).

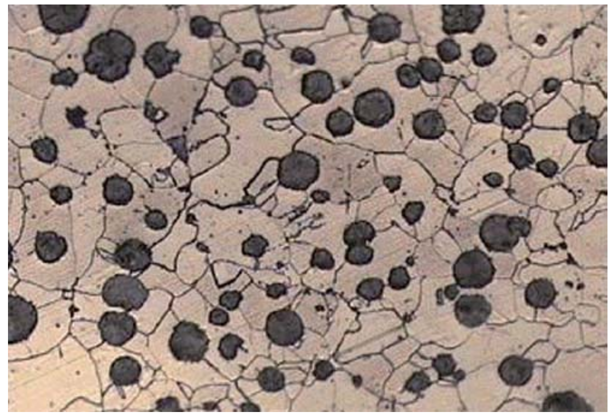

Figure 3. Microstructure of melt M5 (100×, 95% nodularity).

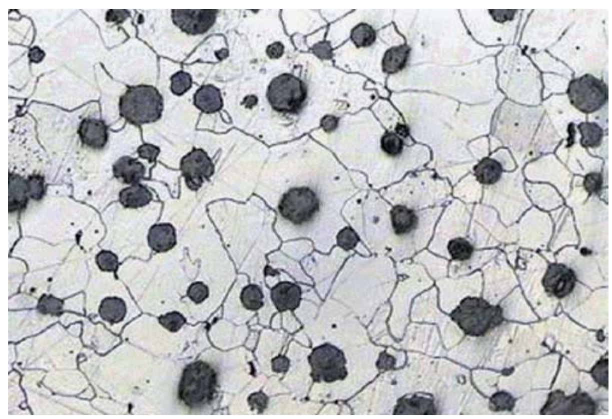

Figure 4. Microstructure of melt M2 (100×, 75% nodularity).

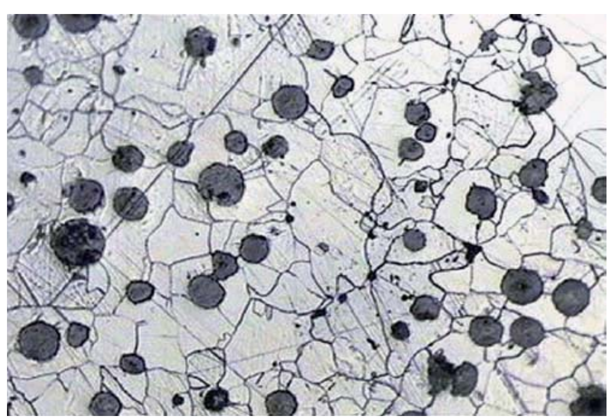

Figure 5. Microstructure of melt M3 (100×, 85% nodularity).

and pouring of metal to achieve optimum mechanical properties with uniform distribution of graphite throughout the matrix in spheroidal shape.

2. Experimental

2.1 Melting and casting

Five melts of SGI castings ('Y' Blocks, ASTM 536) were produced using the tundish tea pot ladle treatment method for this study. All the five melts (M1 to M5) were prepared by taking 100 kg pig iron, 400 kg SGI returns, 500 kg steel scraps, 34 kg coconut charcoal in a 1500 kg capacity medium-frequency induction furnace as per standard procedure and foundry practices. The manufacture analysis of pig iron and steel scrap is listed in Table 1. The carbon percentage of coconut charcoal was found to be 54·75% by analyzing with Strolein apparatus.

Proper inoculation was carried out for all melts except for melts M1 and M2 where instream inoculation was not performed. Both the tapping and pouring temperature was measured by pyrometer for each melt. Proper magnesium treatment was done for each melt and the treated iron was poured in a dry sand mold bonded with furan resin and catalyst. After 48 h of pouring, all castings were cut and machined (as per EN1563 specification) for tensile tests. The final chemistry of each melt was determined by spectrometer (SPECTRO LAB, M9 model) and listed in Table 2. The graphite morphology of each melt was characterized by Digital Image Analyzer. For this, the samples were taken from the centre of the castings. All specimens were ground and polished as per conventional method and etched with 2% nital. Radiographic test was also conducted to check the internal defects of the castings. Samples free from defects were taken for analysis.

2.2 Processing variables

Processing variables are mainly pouring temperature, preconditioning of base iron, inoculation practice, and molding materials. The methods adopted for measuring pouring and tapping temperature and inoculation practice is described in section 2·1.

2.2.1 Preconditioning of base iron

The process of preconditioning was carried out carefully during melting and casting for the melts M1, M4, and M5 immediately before tapping. The melt M5 was preconditioned with adding 0·2% SiC and 0·2% foundry grade FeSi. Similarly, only 0·2% FeSi was added in melt M4 and no preconditioning was carried out for the melt M1.

2.2.2 Molding materials

The molding materials used in the present study are mainly fresh silica sand and reclaimed sand bonded with furan resin and catalyst. The mixed sand is known as furan resin sand which was prepared by self-setting furan binder system in a mixture (Make-Impianti machine fonderia, Italy) taking 1·20% epoxy resin, 45% catalyst, 60% reclaimed sand, and 40% fresh silica sand. Urea formaldehyde/furfural alcohol (OC_4H_3CHO) was used as the foundry-grade resin and the catalyst used was p-toulene sulphuric acid ($CH_3C_6H_4SO_3H$). They are hardened by polymerization at room temperature under the influence of acid catalyst. The sieve analysis of fresh silica sand, reclaimed sand, and physical properties of furan resin sand (as per

Sample	c	Si	Mn	S	P	Fe	Rest elements
Pig iron	4·19	1·74	0·08	0·014	0·051	93·28	Balance
Steel scrap	0·036	0·027	0·112	0·0027	0·0129	99·70	Balance

Table 1. Manufacture analysis of pig iron and steel scrap (wt %).

Melt	C	Si	Mn	S	P	Cr	Ni	Mo	Cu	Mg	CE
M1	3·50	2·05	0·18	0·010	0·021	0·024	0·020	0·002	0·03	0·050	4·18
M2	3·55	2·15	0·19	0·009	0·023	0·021	0·021	0·001	0·026	0·045	4·26
M3	3·60	2·25	0·18	0·011	0·025	0·024	0·023	0·002	0·028	0·041	4·35
M4	3·65	2·35	0·20	0·012	0·027	0·023	0·022	0·001	0·03	0·038	4·43
M5	3·70	2·45	0·21	0·009	0·029	0·027	0·021	0·003	0·029	0·043	4·52

CE: Carbon equivalent.

Table 2. Final chemistry of the melts (wt %).

Type of sand	Moisture (%)	Clay (%)	AFS (GFN)	GD (%)	Density (gm/cc)	LOI (%)	ADV (%)	Sulphur (%)
Fresh	0·05	0·18	41·26	81·80	1·42	0·30	0·47	0·038
Reclaimed	0·10	0·39	43·56	85·40	1·47	4·80	2·52	0·061

GFN: Grain fineness number; GD: Grain distribution; LOI: Loss of ignition; ADV: Acid demand value.

Table 3. Physical properties of fresh silica sand and reclaimed sand.

Dry permeability	>500 (mm head of water)
Dry compressive strength (Kg/cm^2)	32 (After 4 h of sample preparation)
	40 (After 8 h of sample preparation)
	48 (After 24 h of sample preparation)

Table 4. Physical properties of furan resin sand.

ISS 460 standard) was carried out using sand-testing equipments. Results are presented in Tables 3 and 4, respectively.

3. Results and discussion

3.1 Influence of pouring temperature

Pouring colder material will cause excessive dross formation and may result in scrap castings. But melting at higher temperatures has its own problems. Super heating the iron above 1510°C results in reducing the number of nuclei, within the base iron which is finally prone to inverse chill formation. This effect is commonly referred to as 'Monday morning iron' (http://www.ductile.org/magazine/2005_3/ditreatmentopt.htm). Final volume fraction of the austenite dendrites greatly depends on the cooling rate, that is, it increases when the casting diameter is decreased. From Figures 6 and 7, it is clearly observed that the tensile strength, yield strength (YS), elongation, and charpy impact values (at −20°C) are influenced by pouring temperature. The YS decreases with increase in pouring temperature but there is slight decrease in tensile strength. Again, also with increase in pouring temperature, charpy impact values decrease considerably whereas elongation increases. The initial melting was monitored to maintain constant superheat from melt to melt. This is because, if there are melt-down temperature variations, then the unknown inoculants and impurities which are present in all melts can interact in a variable fashion with other impurities from the atmosphere or from the ladle lining to produce variable cast structures (Murthy *et al.*, 1984). As observed in the micrographs (Figures 1–5), the nodularity is increased (except for melt M2) with increasing pouring temperature but there is predominantly decrease in nodule count. Since nodule count determines the quality of iron, an optimum nodule count is required for uniform structure-property correlations. But, due to increase in pouring temperature (from melt M1 to M5), the mechanical properties are not uniform due to decrease in nodule count.

3.2 Influence of preconditioning of base iron

As can be concluded from the experiments, the nucleation potential increases and therefore minimizes the potential for primary carbide formation in the final iron and improves the elongation but there is slight decrease in tensile strength, YS, and impact results. Figures 1, 2, and 3 show the microstructure of the melts M1, M4, and M5 at different preconditioning conditions as described in the experimental procedure. Since proper preconditioning of base iron was performed for the melt M5, it is found that (Figures 3, 6, and 7) there is a better structure-property correlation. Graphite spheroids are well dispersed in the ferritic matrix with 95% nodularity. As far as mechanical properties are concerned, there is a better correlation between UTS, YS, EL, and impact resistance values for the melt M5. Since the melt M1 and M4 are not properly preconditioned, slight irregularities in mechanical properties are observed.

3.3 Influence of inoculation practice

Late inoculation provides nucleation centers for nodular graphite precipitation (Figures 1–3). By doing so, it promotes smaller, more uniformly dispersed and shaped graphite nodules (Figures 4 and 5). Late inoculation in the form of stream helps to improve nodularity (Figures 2 and 3), which helps in reducing the level of magnesium (Swain *et al.*, 2009). Inoculant fading is different from magnesium fading. Inoculant fading results in lower nodule count, chilled edges (carbides), and inverse chill. It can also result in lower nodularity (Figures 1 and 4) even when there is adequate magnesium and rare earths for the section thickness and sulphur levels (Choi *et al.*, 2004; Neri *et al.*, 2003). Nodule count usually increases with proper postinoculation (Swain *et al.*, 2009) or instream inoculation. Though inoculation fades with time, lower temperatures are better for melt inoculation. Considering the properties of the iron M1 and M2 which are not subject to instream inoculation, the tensile strength and elongation did not meet quality index value of ductile

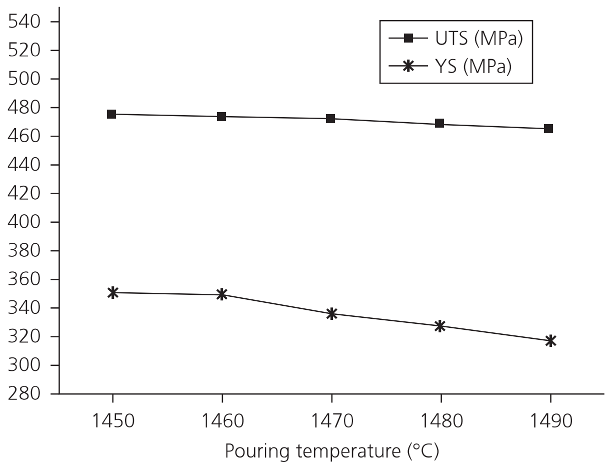

Figure 6. Variation of UTS and YS with pouring temperature.

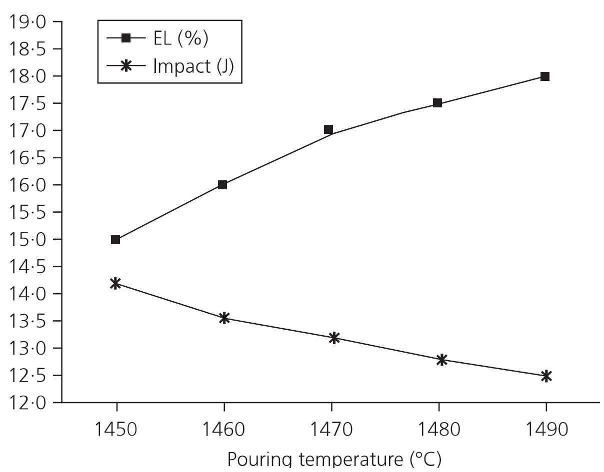

Figure 7. Variation of elongation and impact energy with pouring temperature.

iron. Quality index is a statistical parameter which measures the performance of the material.

3.4 Influence of molding materials

The molding materials used for the experiment is completely described in experimental procedure. For getting desired mold hardness and mold strength, furan resin sand was taken for mold preparation. The combination of fresh sand and reclaimed sand with resin and catalyst gave rise to better compressive strength as described in the experiments. If the step bars have defects such as dross, shrinkage, and inclusion, then the desired properties will not be obtained (Haque *et al.*, 2007). Again, if the sand contains high sulphur, then it creates dross in the casting. Inclusions resulting from sand and slag that are readily seen and recognized as microinclusions will decrease mechanical properties. Ductile iron quality as measured by impact-resistance properties, fatigue endurance limit, and machinability are affected by cleanliness of the iron (http://www.ductile.org/magazine/2005_3/ditreatmentopt.htm). Hence molding materials have significant effect in the production of ductile iron castings. Results listed in Tables 3 and 4 indicate the better physical properties of furan resin sand. This material is used in the present investigation rather than cement sand. From radiographic test and NDT (Non-Destructive Testing), it is clear that maximum defect-free castings are produced using furan resin sand as molding material instead of cement sand.

4. Conclusions

Ductile iron is characterized by having all of its graphite in the form of spheroids. Although this graphite constitutes about 10% by volume of ductile iron, its compact spherical shape minimizes the effect on mechanical properties. The influence of processing variables on mechanical behavior of SGI castings has been investigated. The present study shows that processing variables lead to an increase in nodule count, nodularity, greater ductility, lower strength, and improved toughness. From the experimental results and practice followed, it seems practical and economical that tapping temperature should be as low as possible till maintaining a high-enough pouring temperature (1370±10°C). The specimens of M3, M4, and M5 had lower tensile strength and YS as compared to specimens of M1 and M2. The lower strength appears to be related to lower amount of pearlite in the specimens. The process adopted for preconditioning of base iron for the melt M5 resulted in optimum structure-property (Figures 3, 6, and 7) correlation irrespective of other variables. Similar conclusions may be drawn for the melts M3 and M4 which are properly postinoculated. As far as structure-property correlations are concerned, the molding material (furan resin sand with proper composition as described in experimental procedure) used in the present work may be used in the process industry for manufacturing of spheroidal graphite iron instead of cement sand to achieve optimum property with defect-free castings.

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