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Microstructure Characteristics and Mechanical Properties of Grey Cast Iron at Varied Ferrosilicon Addition

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Abstract: *Inoculation is an essential metallurgical route for controlling solidification conditions of cast iron, consequently, in this study, the influence of varied percent ferrosilicon (FeSi) addition on microstructure and mechanical properties of grey cast iron (GCI) was investigated. A 50Kg capacity rotary furnace was used to melt the charge (Auto engine block scrap, graphite, ferrosilicon (FeSi) and limestone). The casting was produced in a greensand mold with wooden rectangular pattern of length 50 mm and breadth 30 mm. Chemical compositions and carbon equivalent values (CEVs) of the samples were determined, using Optical emission spectrometry (AR 4 metal analyzer) and the expression* $\boldsymbol{CE} = \%\boldsymbol{C} + {}^{\boldsymbol{1}}\!/_{\boldsymbol{3}}\ \%(\boldsymbol{Si} + \boldsymbol{P})$ *respectively. Microstructures of the samples were obtained, using metallurgical microscope (model number NJF-120A). The tensile and hardness properties were measured, using Universal tensile tester and Rockwell hardness tester respectively. From the results, C and Si were the major elements. Other trace elements were Mn, P, S and Al. CEVs of both the control and inoculated samples were less than 4.3%. Microstructure of the control sample was comprised of primary dendrites and graphite flakes, while those of the inoculated samples were characterized by varied amount of more developed primary dendrites, longer graphite flakes and austenite dendrites. Also, a number of small MnS particles were observed in relative amount within the microstructures. Tensile and hardness properties of the FeSi inoculated samples were superior to the control sample. Highest tensile strength and hardness values of 76.62 MPa and 99.89 HRB respectively were obtained at the optimum inoculation of 1.5 wt. % FeSi.*

Keywords: *Greensand, Melts, Microstructures, Primary Dendrites, Graphite Flakes, Austenite Dendrites*

1. INTRODUCTION

Grey cast iron (GCI) is a type of iron with carbon content greater than 2% and a graphitic microstructure, i.e., a large portion of carbon in GCI is present in the form of graphite flakes [1,2]. GCI is characterised by high durability, good malleability, high compressive strength, fatigue resistance, wear resistance, and good damping capacity [3,4,5]. And it is inexpensive relative to the other competitive cast irons such as compacted cast irons (CCI) and ductile cast iron (DCI) [4]. This with the other attractive properties may have accounted for its preference as a candidate material in a wide range of industrial application, especially in automotive industry where it is utilised for producing vital engine components such as engine block, brake, exhaust and piston and ring [6]. However, there is high probability of carbide formation in GCI either at the edges, in thin sections, or along the casting centreline of GCI during solidification, leading to extreme hardness and brittleness with concomitant poor machinability and high susceptibility to failure, particularly when utilized under impact loading condition [7].

Inoculation means introduction of nuclei into the melt so as to control the solidification process or structural formation in the casting in a specific way, inoculation changes the structure of cast iron by altering the solidification process, and it may influence various types of cast iron in different ways [8]. An effective inoculation accounts for reduction in undercooling and increases in the number of nuclei (increase nucleation), which promotes growth of the graphite eutectic, reduces undercooling and minimizes risk of forming hard eutectic carbides in the structure [1,9,10]. Therefore, inoculation practice is an important treatment for achieving high-quality casting. In foundry practice, inoculants added to molten iron prior casting have direct effects on primary structure characteristics such as austenite, carbides, eutectic cells, graphite, and indirectly influences the eutectoid structure, especially pearlite/ferrite ratio, which is dependent on the graphite amount and morphology [1,11,12]. Promotion of Type A graphite formation, prevention of undercooled graphite and rosette graphite formation, modification of graphite morphology to a uniform “A” type structure and reduction of section sensitivity between thin and thick sections within the same casting have been achieved through inoculation practice [13,14]. Effective inoculation depends on the presence of minor elements, including calcium (Ca), barium (Ba) and strontium (Sr) [15,13], and according to Stan et al. [14] available commercial inoculants are based either on a ferrosilicon alloy (blend of graphite and ferrosilicon) or a mixture of ferroalloys.

No doubt, a plethora of studies on grey cast iron inoculation are found in literatures, but the aspects of optimum inoculant(s) requirements is still relatively inadequate. Consequently this work is aimed at evaluating the influence of varied percentage of silicon based inoculant (0.75% silicon ferrosilicon, containing 1% and 0.2% calcium) on the microstructure characteristics and mechanical properties of grey cast iron, and this is with the sole objective of obtaining optimum percent of inoculant requirement(s) that gives the desired/ best microstructure, and hence mechanical properties (tensile strength and hardness).

2. RELATED WORKS

Riposan et al. [1] investigated the effect of 0.03 wt. % of Al, Zr, and Ti in gray irons, and reported that Al and Zr have visible beneficial effects, by lowering the degree of eutectic undercooling, chilling tendency, undercooled graphite, and free carbides amount. In both the uninoculated and inoculated irons, Ti seems to be beneficial as graphitizing action only in un-inoculated irons, but at lower relative power compared to Al and Zr. Dhruv et al.[16] investigated effect of Ca and Ba containing ferrosilicon inoculant on microstructure and tensile properties of IS-210 and IS-1862 cast iron, and they revealed that both Ca and Ba based inoculants were effective in obtaining uniform distribution of flaky and nodular graphite in IS-210 and IS-1862 cast irons respectively. However, the inoculants showed marginal effect on tensile strength of the cast irons. Fengzhang et al. [17] investigated the effect of FeSi 75+RE and FeSi 75+Sr inoculants on mechanical properties, machinability and sensibility of grey cast used in cylindrical block, and reported that the 60%FeSi 75+40%RE inoculant treated grey cast iron showed a consistent tensile strength of about 295MPa with good hardness and microstructural characteristics. While the 20%FeSi75+80%Sr inoculated grey cast iron showed best machinability, lowest cross section sensibility and least microhardness difference.

Hirs et al. [18] studied effects of inoculation, cooling rate and composition on the microstructure of grey cast iron. Three iron with almost the same chemical composition were used for the investigation. Melt 1 was comprised of 10% steel scrap, 39.4% pig iron, 49.2% grey iron return and 0.6% silicon carbide, melt 2 was comprised of 38.8% steel scrap, 9.9% pig iron, 47.9% grey iron return and 1.6% silicon carbide and melt 3 was comprised of 0.00% steel scrap, 0.00% pig iron, 99.2% grey iron return and 0.06% silicon carbide. And from each of the melt, one uninoculated and inoculated stepped test casting with wall thickness of 5,10, 20, 45 and 65 mm were produced. 0.23 % inoculant was introduced in the melt stream during pouring in the mould. They reported that the type, size and distribution of graphite flakes were not significantly dependent on the charge composition, and the structure of the metal matrix, carbides, precipitation and type, size distribution of graphite flake were largely dependent on the wall thickness. And with increasing wall thickness, the cooling rate was decreased and the graphite flakes were changed from D and E through B to type A. Carbide formation was observed to occur at the edge region of 5 mm thick wall, and the carbide content was significantly reduced by inoculation. Also, inoculation was observed to increase the proportion of type A graphite flake in middle of the 5 mm thick wall and in the wall with thicknesses of 10 mm, 20 mm, 45 mm and 65 mm. While the proportion of types B,D and E graphite flakes were significantly reduced.

Diego et al. [19] evaluated of 1M -22 with FeSi-Ba/Zi; G-20 and FeSi-Ba; IMSR75 with FeSi-Sr on the machinability characteristics of parts, microstructure and mechanical properties of grey cast iron. They reported that IMSR75(FeSi-Sr) can be suitably used to produce grey cast iron relative to the other experimented inoculants G-20 (usual) and IM-75(FeSi-Ba/Zr), and the superior performance of IMSR75(FeSi-Sr) was attributed to the Sr, which they said is more efficient in the formation of microstructure with more eutectic cells. Izudin and Igvar, [20] investigated the effect of inoculant amount and casting temperature on metal expansion and penetration in grey cast iron. Three different inoculants amounts (0.05%, 0.15% and 30%) were used. From the obtained eutectic cells and distribution, they concluded that nucleation of the eutectic cells played an important role in the formation of expansion penetration. Influence of melt casting temperature showed a clear coupling between low amount of inoculant and casting free from penetration. At inoculant addition of 0.15% and 30%, the penetration was decreased with reduced pouring temperature. And it was clear from the microstructure analysis that penetration is associated with a mixture of large and small eutectic cells. The best results were obtained using low inoculant addition (0.05%), and using temperature above 1390^{o}C, no penetration, bulb formation or shrinkage were found on the casting.

Szczesny et al. [21] investigated the possibility of producing large size or heavy- weight castings of plate in a vertical arrangement with the aim of achieving evenly distributed graphite flakes, leading to reduction in volumetric fraction of type D graphite. Different inoculants were used for the study, and inoculant with fine granulation requires dosing that prevents its oxidation on the surface of the molten melt in the crucible, and steel ball was used for the purpose. From the report, the use of steel ball was revealed to weaken the inoculation effect by producing smaller number of graphite eutectic grains; however, it affected the primary crystallisation of austenite. The inoculated method with the use of steel ball enhanced homogeneity of the cast iron microstructure. And the use of zircinic inoculant caused a significant decrease in volume fraction of D-type graphite to the level of 3% in standard cast shaft and gave the lowest value of degree of undercooling. Reyes-Castellanos et al. [22] carried out experimental assessment of grey cast iron produced by inoculant injection, argon was used as conveying gas into the iron bath. The report showed that despite low graphitizers element and manganese contents in the grey cast iron, type-A graphite distribution for the particle size fine (211 to 297) could be obtained. The number of eutectic cells was found to increase as inoculant particle size and casting thickness were decreased. The injection approach and the used inoculant were found to promote adequate features, which led to lower amount of undercooled graphite, free cementite and ferrite phases. Saliu et al. [23] investigated effect of inoculation on varying wall thickness of iron recycling, and the result as evident in the eutectic cells and graphite flakes observed in each of the microstructure revealed that the inoculant has greater influence on the different wall thickness. And they concluded that eutectic cells decreased as the wall thickness was increased. Borse and Manguther, [24] carried out a review on grey cast iron inoculation, and observed that properties of the base metals were improved with variation in percentage of the inoculants and change in composition of the base material.

From the reports of the past researchers on inoculation treatment of melt, it is obvious that this metallurgical approach is visibly a viable parameter for achieving sound casting. This is because during solidification, the cast iron reaches the eutectic temperature at which solidification is expected to occur based on stable iron - graphite diagram. In practice, however, equilibrium condition never occurs, due to inherent degree of undercooling. Promotion of solidification according to the stable system iron-carbon, and hence preventing undercooling below the metastable temperature where iron carbide (Fe_3C) are formed requires inoculation treatment [32]. While derivable advantages of inoculation of castings are numerous, some of these, for grey cast iron are (i) chill reduction (ii) graphite formation promotion, (iii) formation of fine graphite reduction (iv) uniform structures in various section promotion and (v) mechanical properties and machinability improvement [25].

3. METHODOLOGY

3.1 Materials

Auto engine block scraps used for this research were obtained from Grand Foundry, Ikeja, Lagos State, Nigeria. The other materials (graphite, ferrosilicon (FeSi) and limestone) were procured from relevant vendors. Chemical compositions of the Auto engine block scrap was determined by optical emission spectrometry (AR 4 30 metal analyzer), and the results are presented in Table 1.

Table 1: Chemical composition of auto engine block scrap

Element	Composition (%)		
C	3.97	Mg	0.0033
Si	1.94	B	<0.0005
Mn	0.87	Sn	0.0083
P	0.088	Zn	0.0081
S	0.131	As	0.020
Cr	0.163	Bi	<0.0015
Ni	0.058	Ce	<0.0030
Al	0.0056	La	<0.0033
Cu	0.138	Fe	92.5
Co	0.015		
Ti	0.0015		
Nb	<0.0025		
V	0.0099		
W	<0.010		

3.2 Green Sand Mould Preparation and Casting

Greensand or wet mold was prepared by mixing silica sand with bentonite and coal dust in the presence of adequate water [14]. A wooden rectangular pattern of length 50 mm and breadth 30 mm was used, while ensuring adequate shrinkage, machining, draft, rapping and distortion allowance. Afterwards, the cope was assembled on the drag and some loads were placed on top of the assembly to apply pressure for support against melt pressure when pouring. The iron scrap and lime (fluxing agent) were charged into a 50Kg capacity rotary furnace. The furnace was preheated for 60 to 70 minutes to allow for uniform melting rate [1,23]. Thereafter, the furnace was charged and heated to high temperature, and complete melting of the charge was achieved at 1,470^{o}C. The furnace temperature was measured at regular interval with optical pyrometer. Silicon based inoculant with 0.75% silicon ferrosilicon, containing 1% and 0.2% calcium and particle size 1.2 mm were prepared. The first melt, being the control sample was tapped into the ladle without inoculation, and 0.50 wt.%, 1.00 wt.%, 1.50 wt.% and 2.00 wt.% of the inoculant was introduced to the metal stream of the second, third fourth and fifth melts respectively to produce four different inoculated samples. Both the control and inoculated samples were given adequate time to gradually transform into solid castings at the room temperature (23^{o}C) in the mould. This was necessary to avoid any hot shaking effects on the solid state solidification. Thereafter, the castings were knocked out of the greensand mould [26]

3.3 Chemical Compositions and Carbon Equivalent of the Samples

Optical emission spectrometry (AR 4 30 metal analyzer was used to analyse the chemical compositions of the GCI samples and the result is shown in Table 2 respectively. And the carbon equivalent values (CEVs) of the samples were calculated using the expression in Equation 1

$$\mathrm{CE} = \%\mathrm{C} + {}^{1}\!/_{3}\ \%(\mathrm{Si} + \mathrm{P}) \tag{1}$$

3.4 Microstructure Examinations

Metallography specimens were prepared based on ASTM E3-11 [27]. Samples for the specimens were consecutively ground on a water lubricated silicon carbide abrasive papers of 180, 240, 320, 400 and 600 grit sizes, and polished on 15cm rotating discs of a POLIMET universal polishing machine with synthetic velvet polishing clothes impregnated with 1 µm Alumina paste. Thereafter, they were etched with 2% nital solution, using swabbing method with cotton wool soaked in the etchant and rinsed with water[27]. Metallurgical microscope (model number NJF-120A) to obtain the different microstructures of the grey cast iron.

3.5 Tensile and Hardness Testing

The tensile test samples were machined to standard dimensions (Figure 1). The test method adopted was ASTM E8-04 [28]. The test sample was mounted at its ends onto the holding grips of the Universal Tensile Testing Machine. Each sample was subjected to tension till fracture, after which tensile strength and percentage elongation were taken. Hardness specimens with dimension 20 mm length, 20 mm breadth and 4.5 mm thickness (Figure 2) were prepared in accordance with ASTM E384-11 [29] standard. Universal Rockwell hardness tester model 8187LKV was used. The specimen was placed on the anvil and moved up until it came in contact with the diamond cone indenter, the dial gauge was set to zero using minor load of 10kg. Thereafter, major load of 150kg was applied on the specimen, and the corresponding hardness value was measured on the C-scale. Three indentations were made with gap of about 3 mm in-between and the average values were recorded.

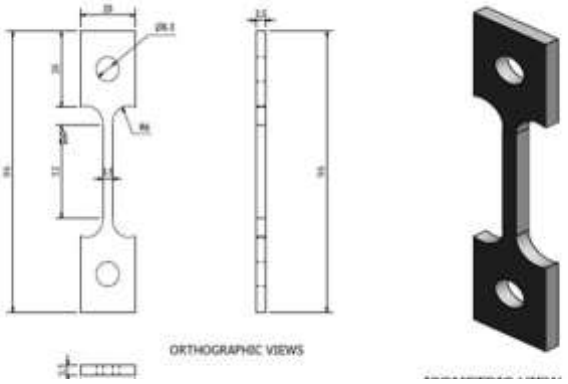

Figure 1: Tensile test specimen

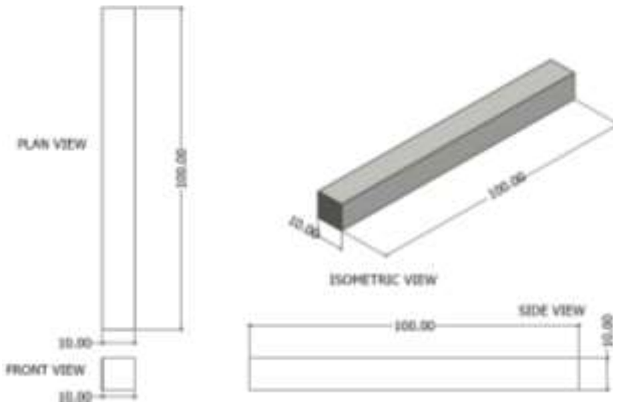

Figure 2: Hardness test specimen

4. RESULTS AND DISCUSSIONS

4.1 Chemical Analysis

Chemical composition of the grey cast iron samples is shown in Table 2, and from the results, the contents of major elements (carbon and silicon) for the uninoculated sample are 3.08% and 2.45% respectively, and those of the inoculate samples are in the range of (3.01-3.04%) for carbon and (2.63-2.79%) for silicon. The other residual elements [(manganese (Mn), phosphorous (P), sulphur (S), and aluminium (Al)] are kept at negligible low levels. The observed increased graphitization potential of the inoculated samples with increasing addition of the inoculant was due to increasing presence of silicon, because graphitization potential of liquid metal is dependent on the carbon equivalent, and in particular silicon content [30]. The manganese and sulphur contents of all the samples were at a beneficial level range [13]. Both samples (control and inoculated) hypo-eutectic grey cast irons, because their CEVs were less than 4.3% [31]. And the observed variations in CEV wt. % of the inoculated samples were expected, and are attributable to inoculation effects [9].

Table 2: Chemical composition of the grey cast iron samples

Ferrosilicon Addition (wt.%)	Chemical composition (wt. %)						CE (wt.%)
	C	Si	Mn	P	S	Al	
Contl.	3.080	2.450	0.234	0.088	0.145	0.001	3.150
0.500	3.010	2.630	0.220	0.069	0.133	0.008	3.080
1.000	3.100	2.780	0.201	0.060	0.129	0.008	3.170
1.500	3.060	2.860	0.101	0.071	0.118	0.009	3.100
2.000	3.040	2.790	0.101	0.064	0.123	0.009	3.100

4.2 Microstructure

From Figure 3 (a-e) microstructure of the control (0.00 wt. % FeSi) sample is characterized by primary dendrites and short graphite flakes. The short graphite flakes were promoted by rapid solidification. This is because flake formation is primarily a function of cooling rate [1, 31]. Microstructures of the varied weight percent ferrosilicon (wt.% FeSi) inoculated samples are characterized by a number of more developed primary dendrites, austenite dendrites and longer graphite flakes(Plate 1(a-e), which resulted from influence of FeSi addition. This is because inoculation is meant to sustain graphite formation instead of cementite and to discourage undercooled graphite morphologies, including Type B, D, E ASTM [14,31]. In general, CE transforms the effect of elements on the graphite precipitation into relative content of carbon [14]. Therefore, the amount of graphite within the microstructures may have partly been influence by the CE [8]. The observed relative number of small MnS particles of within the microstructures acted as effective nuclei for primary austenite and graphite [8].

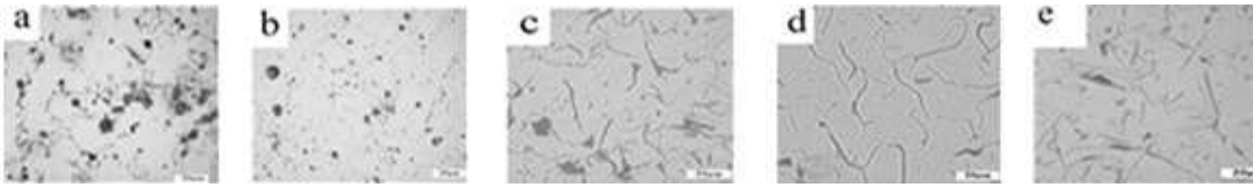

Figure 3: Optical microstructures of (a) Control, (b) 0.50 wt. %, (c) 0.10 wt. %, (d) 1.5 wt. % and (e) 2.00 wt. % FeSi inoculated grey cast iron samples at Mag. 200X.

4.3 Tensile and Hardness Properties

From the tensile result in Figure 4, the high tensile strength values of samples b, c, d and e relative to sample e (refer to Figure 3) may be attributed to effects of ferrosilicon addition [8, 9, 10], and improvement in tensile strength of the inoculated samples with increasing FeSi addition was due to increasing presence of primary dendrites [14]. The highest tensile strength of 76.62 MPa that was revealed by sample with 1.5 wt. % FeSi addition resulted from increased presence of the most developed amount primary dendrites [6]. While the subsequent decrease in tensile strength value that was revealed by the sample with higher FeSi addition of 2 wt.% may be attributed to primary dendrite growth suspension by primary austenite that resulted from increased presence of MnS particles. Accordingly, the MnS particles acted as effective nuclei for the primary austenite graphite [1]. In addition, the obtained improved tensile strength of the inoculated GCI samples was the decrease in CE values (graphite amount) [14].

Also, consistent gradual increase in average hardness values of the inoculated samples over the control sample with increasing wt. % FeSi addition as shown in Figure 5 may be attributed to controlled cooling rate solidification conditions that resulted from inoculation. While highest hardness value of 99.98 HB that was obtained at 1.5% FeSi was due to increased amount of carbide formation that resulted during melt solidification [7, 32]. Conversely, subsequent drop in hardness with further wt. % FeSi addition at 2% was accounted for by decreased carbide formation that resulted from relative slow cooling effect of inoculation [7].

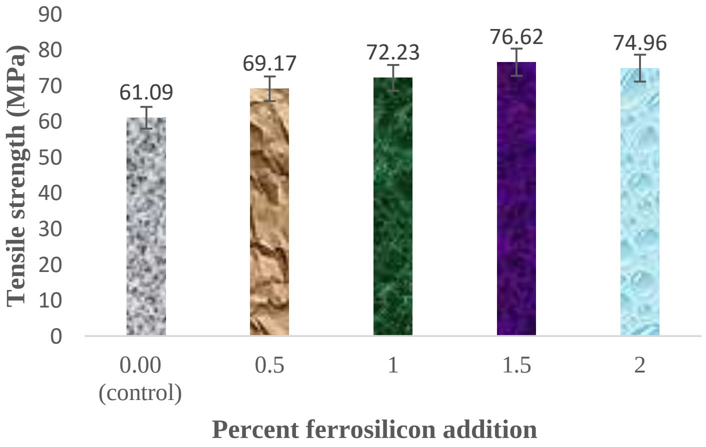

Figure 4: Tensile behaviour of the grey cast iron samples at varied per cent ferrosilicon addition

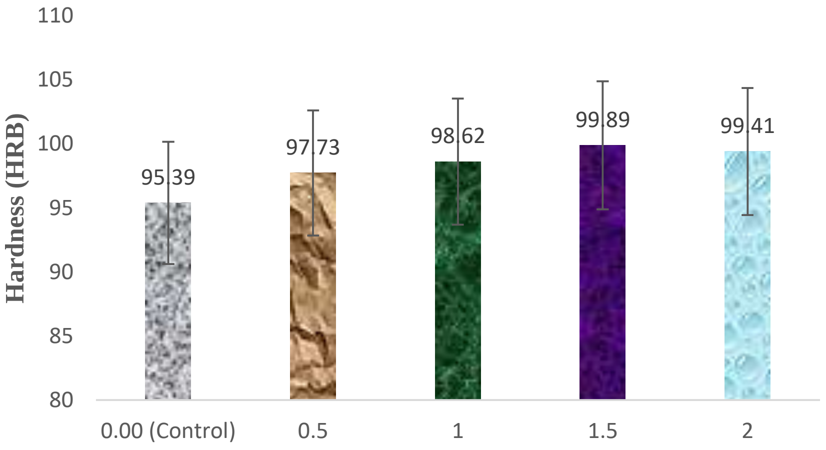

Figure 5: Hardness behaviour of the grey cast iron samples at varied percent ferrosilicon addition

5. CONCLUSION

From the results obtained, the following conclusions were drawn:

i. Carbon and silicon were the major elements, while the other elements (Mn, P, S and Al) were in trace quantities.
ii. The calculated carbon equivalent values of both control and inoculated samples were less than 4.3%. As a result, the samples are hypoeutectic grey cast iron.
iii. Microstructure of the control (0.00 wt. % FeSi) sample was characterized by primary dendrites and graphite flakes, those of the FeSi inoculated samples were characterized by varied amount of more developed primary dendrites, longer graphite flakes and austenite dendrites.
iv. A number of MnS small particles were observed in relative amount within the microstructures all the samples.
v. Generally, tensile and hardness properties of the FeSi inoculated samples were superior to the control sample. Highest tensile strength value (76.62MPa) and hardness value (99.89HRB) were both obtained at 1.5 wt. % FeSi. Hence, 1.5 wt. % FeSi requirement gave optimum microstructure and, in consequence the highest mechanical properties (tensile strength and hardness).

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