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Effect of Cu and Mn on the Mechanical Properties and Microstructure of Ductile Cast Iron

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Abstract
This paper described the method used for producing ductile cast iron (SGI). The processing parameters affecting the production of SGI were studied. These parameters include chemical composition, castings thickness, mechanical properties, alloying elements and microstructure. The chemical composition of producing SGI was optimized. The nodularity was increased with increasing the percentages of Mg content and with decreasing the castings thickness. The amount of pearlite and mechanical properties were increased sharply with increasing Cu and Mn contents in the produced SGI. Empirical equations were correlated to indicate the relations among nodularity, Mg content and other parameters. The results shown also as the post inoculation increased the metallurgical quality was improved. The suitability of SGI as automotive engine was tested and different empirical correlations were obtained
Key words- Nodular cast iron, nodularity, wear resistance, mechanical properties and microstructure of SGI

I. Introduction

Ductile cast iron is part of a group of cast iron which can be produced to have a wide range of properties through control of the microstructure. The morphology of carbon in ductile cast iron is present as tiny spheres (nodules) in the as cast condition [1]. This structure is developed from the melt and the carbon forms into spheres when cerium, magnesium, sodium, or other elements are added to a melt of iron with a very low sulfur content that will inhibit carbon from forming. In ductile cast iron, eutectic graphite separates from the molten iron during solidification in a manner similar to that in which eutectic graphite separates in gray cast iron [2, 3]. Cast iron containing spheroidal graphite is much stronger and has higher elongation than gray iron or malleable iron. It may be considered as a natural composite in which the spheroidal graphite imparts unique properties to ductile cast iron [4, 5]. The relatively high strength and toughness of ductile cast iron give it an advantage over the other types of cast iron in many structural applications. Since, the ductile cast iron does not require heat treatment to produce graphite nodules as malleable iron does to produce temper-carbon nodules [6, 7]. Although, the other types of cast iron family may have superior individual properties, which might make them the material of choice in some applications, none have the versatility of ductile cast iron, which often provides the designer with the best combination of overall properties [8-11]. This is especially evident in the area of mechanical properties where ductile cast iron offers the designer the option of selecting high ductility, with grades guaranteeing more than 18% elongation (as high as 25 %), or high strength, with tensile strengths exceeding 825 MPa. Austempered ductile cast iron offers even greater mechanical and wears resistance, providing tensile strengths exceeding 1500 MPa [12]. Ductile cast iron is used for many structural applications, particularly those requiring strength and toughness combined with good machinability and low cost. The automotive and agricultural industries are the major users of ductile cast iron castings [13, 14, and 15]. Alloying elements such as chromium, nickel, molybdenum, copper, vanadium, and boron act as carbide formers, as pearlite stabilizers, or as ferrite promoters. Alloys are controlled to the extent needed to obtain the required mechanical properties and/or microstructure in the critical section(s) of the casting [3, 16, and 17]. The shape and nodule count, (expressed as the number of graphite nodules/mm^2), influences the mechanical properties of ductile cast iron. Nodule count is a sensitive parameter in ductile cast iron production. Generally, the high nodule count indicates good metallurgical quality, but there is an optimum range of nodule count for each section size of casting, and nodule counts in excess of this range may result in a degradation of properties [18, 19].

The aim of this work is to study the effect of alloying elements and castings thickness, on the microstructure, wear, and mechanical properties of the produced ductile cast iron. The relations among the alloying elements, Nodularity, Perlite% and mechanical properties were correlated.

II. Experimental Work

The materials used in this work are: Pig iron (4.2 % C, 0.2 % Si), steel scrap (0.2% C, 0.2% Si), carbon (90 %C), ferro-silicon (0.5 %C, 75 %Si), pure copper (99.9 %Cu), ferro-manganese (0.5 C%, 75%Mn) and nodulizer (45% Si, 5.5%Mg).

P.I and S.S were weighed - about 6 kg- and charged into induction furnace crucible. The weighed charge was completely melted and the slag was skimmed using a common de-slagging agent. The molten cast iron was hold at elevated temperature, then poured into thermal analysis crucible to estimate carbon equivalent (CE), C% and Si% content. Thereafter, charging and melt-down chemistry adjustments were made using a thermal analysis technique. Also, chemical analysis chill pieces were taken from each casting to spectrum analysis before adding nodulizer. Liquid treatment using Fe-Si-Mg (nodulizer) was added by method of injection at temperature 1400 ^{o}C. The treated molten metal was poured into thermal analysis crucible to estimate CE, C% and Si% content after adding nodulizer, then 0.2% of post inoculating agent was added. After 3 minute, the liquid metal was poured into chill piece and sand molds (steps mold) to give different thickness as shown in Fig.1. The specimens were taken from sand molds and prepared for metallographic, wear and mechanical tests. The castings were etched using Natal (3%HNO_3 in methanol solution) for 3 min. for Pearlite% determination and the Nodularity results were compared with the standard charts according to ASTM 2567-11. The chemical analysis was performed using a spark emission spectrometer. The specimens also were cutting according to ASTM to carry out different mechanical properties under room and elevated temperature; tensile, wear, and hardness. The test pieces used for tensile testing were machined from as-cast SGI produced samples according to ASTM E 8M at room temperature. Wear test was performed using Pin-on-Disk wear testing machine with load 47.2 N, 96 rpm, distance 4000 m and the sliding velocity (0.2 m/sec) with normal and Argon atmosphere at different temperature [20]. The experiments were repeated at different parameters; Mg%, thickness, Mn%, Cu%, at pouring time 3 min., and pouring temperature 1400 ^{o}C, The results of these experiments will be indicated as follows.

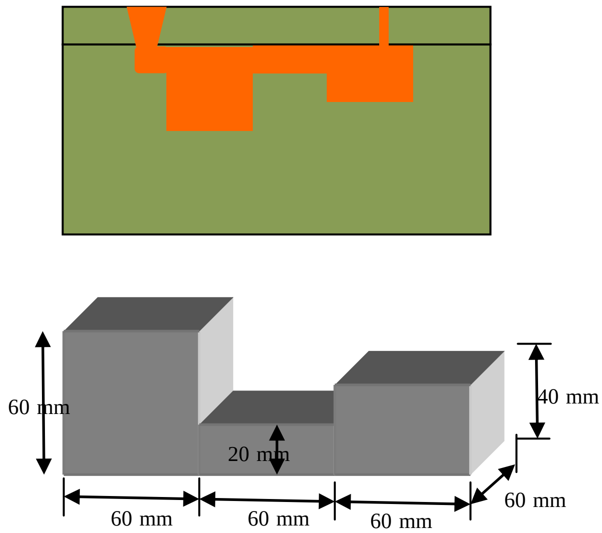


Fig.1. Schematic diagram for mold pattern and experimental setup to make different thickness

III. Results and Discussion

1- The chemical analysis for the producing SGI

The chemical composition of the produced nodular cast iron is illustrated as shown in Table 1. The optimum CE must be selected as a function of section size of the casting. For a given section size, too high a CE will result in graphite flotation, as in the case of spheroidal graphite cast iron, while too low, a CE may result in increased chilling tendency. Also, it is important that the sulfur content not increased, because the higher the sulfur content, the more alloy is required for melt treatment; the sulfur is reacted with Mg and hinder the nodulization process. Typical residual sulfur levels after treatment must be 0.01 to 0.02% [15].

TABLE 1- CHEMICAL COMPOSITION OF THE PRODUCED DUCTILE CAST IRON

Element	**CE**	**C**	**Si**	**Mg**	**Cu**	**Mn**	**S**
Range,%	4.0-4.7	3.0-3.9	1.8-2.8	0.01-0.05	0.01-1.0	0.1-0.6	0.011

2 The effect of Magnesium (Mg%)

The magnesium content is the most important element for the morphology of eutectic carbon in cast iron. The effect of Mg% on the nodularity % in the produced nodular cast iron at different thickness is indicated in Fig. 2. It can be noticed that the nodularity is increased linearly with increasing the Mg%,. The nodularity is more than 80% in the range from 0.025 to 0.035 at thickness 20 mm. Also the results indicated that the nodularity is decreased with increasing castings thickness, and this decreasing is caused by some oxidation of Mg due to the decreasing of solidification rate with increasing of thickness [20].

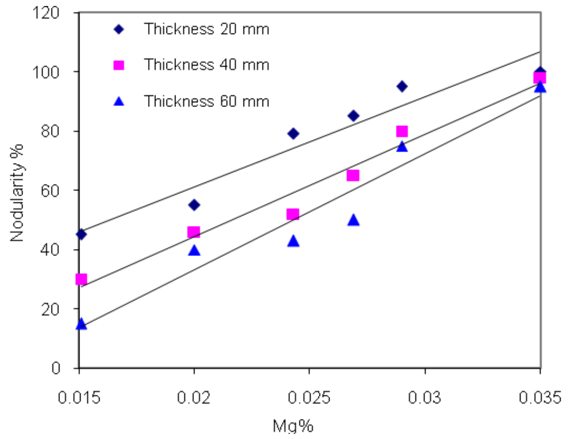


Fig. 2 Effect of Mg% contents on the nodularity% of the produced SGI specimens

3 Effect of Copper

The effect of Cu content on the amount of pearlite% in the produced SGI was studied from 0.01 to 1.0 % at different thickness as shown in Fig. 3. The results indicated that the amount of pearlite is increased sharply with increasing the Cu content in the produced SGI, but at the same Cu content, the amount pearlite is slightly decreased with increasing the casting thickness. The amount of pearlite was correlated as a function of Cu contents as follows:

Pearlite%= 61 Cu – ¼ X + 23
0.01%<Cu<1.0%
20 mm <X<60 mm

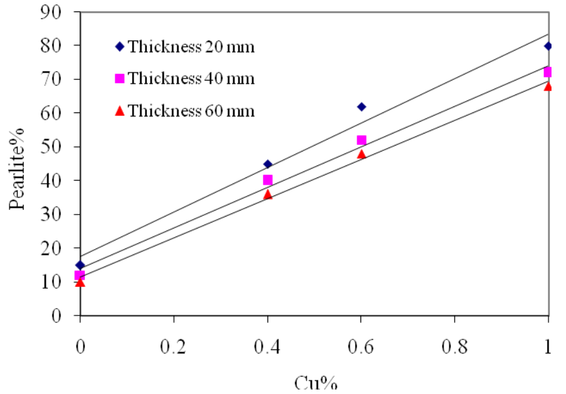


Fig.2. Effect of Cu content on the pearlite % in SGI at different thickness

Fig.3 shows some etched micrographs with Nital (3%HNO3 in methanol solution) for 3 min. using light microscopy. These specimens were done at thickness 40 mm, Mg content 0.024% and at different Cu contents. Fig.3 (a, b, c and d) shows typical microstructure of SGI specimens contain 0.01, 0.4, 0.6 and 1.0 Cu%. This figure illustrated that the SGI were presented as a ferritic-pearlitic matrix (containing 11, 39, 51 and 72% pearlite % respectively). Also, the size of carbon nodule increases with increasing Cu% contents. Although, the effect of Cu on the size of nodules is unavailable in open literature, but, it may be the presence of Cu fads or hinder the efficiency of inoculation process.

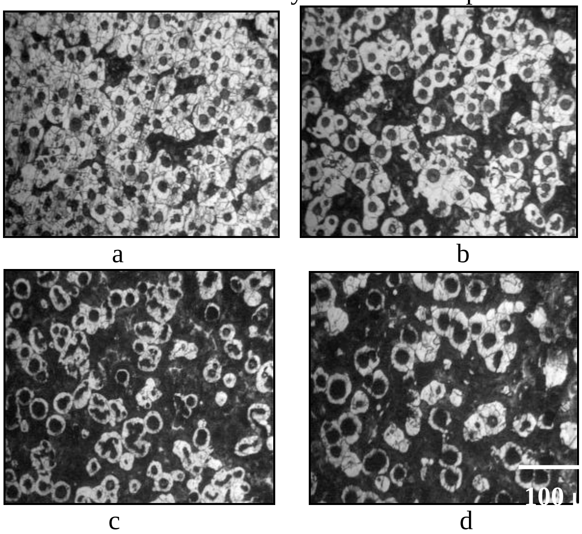


Fig. 3 Micrographs of the produced SGI at thickness 40 mm, 0.024% Mg and at different Cu contents
a) 11% pearlite b) 39% pearlite. c) 51% pearlite d) 72% pearlite

4 Effect of Manganese

Effect of Mn content on the Pearlite % in the produced SGI at different thickness was studied from 0.1 to 0.6%. As shown in Fig. 4, the Pearlite % is increased with increasing Mn content. But the Pearlite % is decreased with increasing thickness at the same Mn content. The amount of pearlite was correlated as a function of Mn content and thickness (X) as follows:

Pearlite%= 86 Mn% – 1/5 X + 15
0.1 %<Mn<0.6%
20 mm <X<60 mm

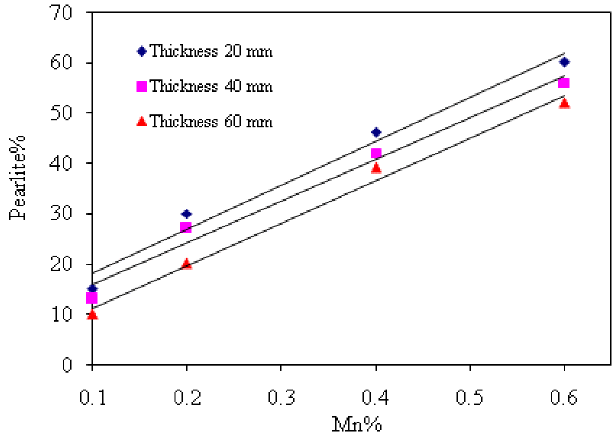
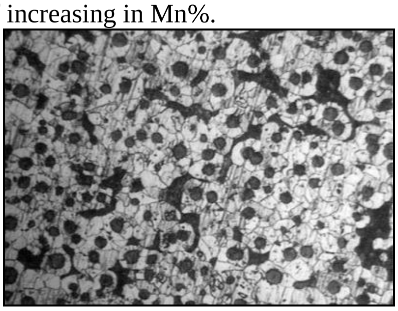


Fig. 4 Effect of Mn content on Pearlite in SGI at different thickness

Figure 5 shows two micrographs of the produced SGI etched with Nital for 3 min, at thickness 40 mm, Mg contents 0.024% and at different Mn%. Typical microstructure in Fig.5 (a, b) for SGI specimens contain 0.1, and 0.6 Mn%. It can be seen that SGI which were present in a ferritic-pearlitic matrix(containing 13, and 55% pearlite respectively, but, it no noticeable any changes in the size of carbon with increasing of Mn% contents. Typical microstructures in Figures 3 and 5 illustrate that the effect of increasing in Cu % is larger than the effect of increasing in Mn%.



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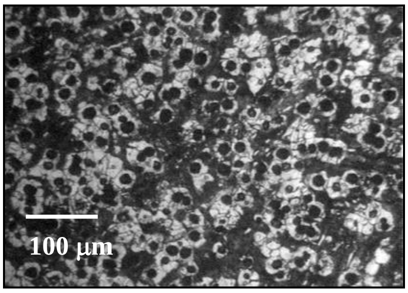
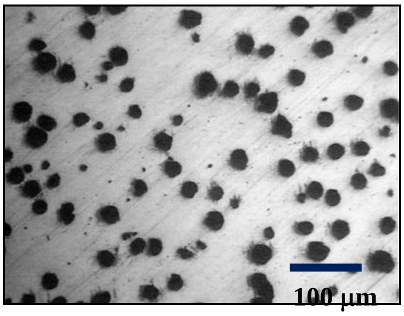


b

Fig. 5 Micrographs of the produced SGI at 40 mm thickness and 0.024Mg% with a) 0.1 Mn%, 13% pearlite b) 0.6 Mn%, 55% pearlite

5 Effect of post inoculation

Fig. 6 shows two micrographs of the produced SGI with 40 mm thickness and 0.035 Mg%, inoculating with 0.1 and 0.2 of post inoculation (Fe-75%Si). From this figure, it can be seen that the size of graphite nodules in inoculating using 0.1 of post inoculation (Fig. 6a) is bigger than the graphite nodules using 0.2 of post inoculation (Fig.6b). According the ASTM E2567-11 the micrograph Fig.6a contains about 400 Noduls/mm2, while the micrograph Fig.6b contains about 1550 Noduls/mm2. This means good metallurgical quality will be obtained as the nodularity increased.



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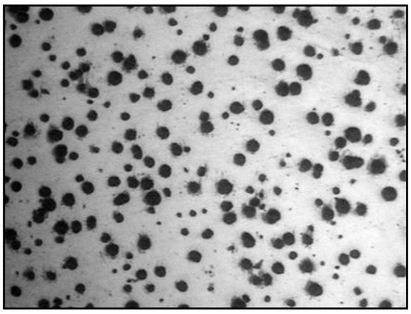

b

Fig. 6 Micrographs of the produced SGI with 40 mm thickness and 0.035 Mg%

a) Inoculating with 0.1 Fe-Si (400 N/mm^2)
b) Inoculating with 0.2 (1550 N/mm^2)

6 Mechanical properties of the produced SGI

6.1 Ultimate tensile strength (UTS) and Hardness (BHN)

Effect of Mg% on ultimate tensile strength and hardness at different thickness size 20, 40 and 60 mm was studied as shown in Figures 7, 8. Fig. 7 indicates that, the ultimate tensile strength is increased with increasing Mg content for all section sizes, and this is due to increase the nodularity. Effect of Mg content on tensile strength is decreased with increasing the casting thickness. This decreasing is due to decrease the solidification rate which leads to some Mg fading and decreasing the nodularity.

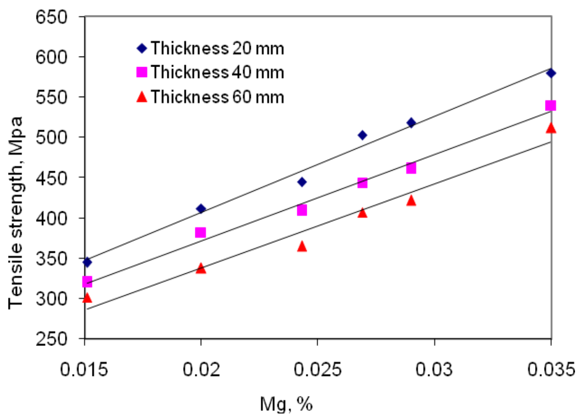

Fig 7 Effect of Mg content on tensile strength at different size

Also from Fig. 8, the hardness is increased linearly by increasing Mg% and nodularity. The UTS and BHN are correlated as a function of Mg content and thickness (X) in the produced SGI as follows:

UTS, Mpa = 11000 Mg% + 240- 2X
Hardness, BHN= 6300 Mg% + 100-X
0.015%<Mg<0.035%
20 mm <X<60 mm

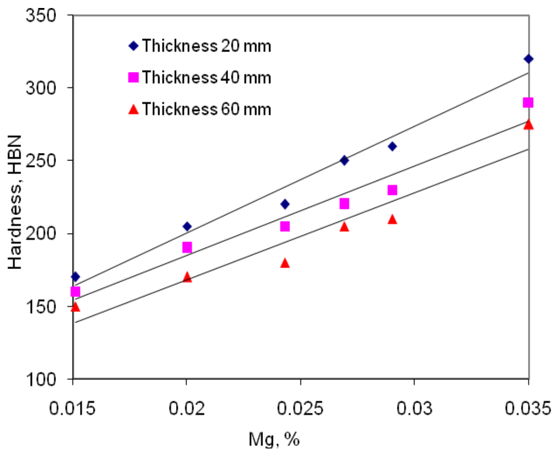

Fig 8 Effect of Mg contents on Hardness at different size

6.2 The effect of nodularity and Mg% on wear at elevated temperatures

In order to determine the suitability of SGI as automotive engine, a series of scuffing tests were conducted to compare the wear resistance of various SGI microstructures and compositions with commercially available cylinder liner materials. So, the effects of Mg % and nodularity % in the produced SGI alloys on wear resistance were investigated as shown in Figures 9, 10. From these Figures, it can be seen that the amount of wear losses is decreased slightly with increasing of Mg% and nodularity%. The decreasing of wear amount in the produced SGI alloys is due to increase of its strength. While at same Mg% and nodularity, the wear amount is increased with increasing temperatures in normal atmosphere, but when the Ar atmosphere is used, the wear is little decreased at same temperature and nodularity, because Ag presence, the chance for oxidation is might be decreased than in presence of normal atmosphere [20]. The wear amount, mg/cm2 was correlated as a function of Mg% and nodularity (N) at room temperature in the produced SGI as follows:

Wear amount, mg/cm2 = -507.2Mg% + 32.37
Wear amount, mg/cm2 = -0.157 N + 31.70
0.015%<Mg<0.035%
45% <N<100%

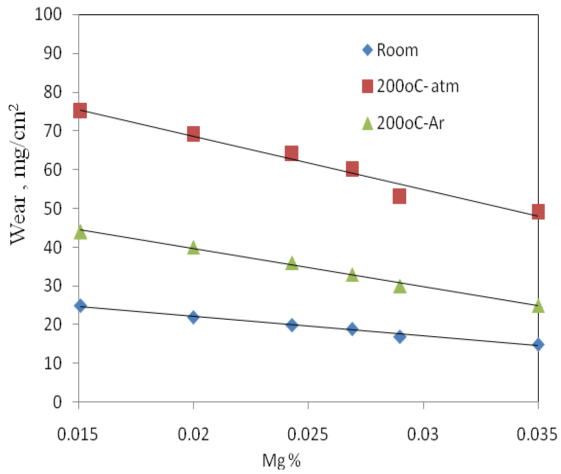

Fig. 9 Effect of Mg% on the wear of the produced SGI specimens at different elevated temperatures and atmospheres

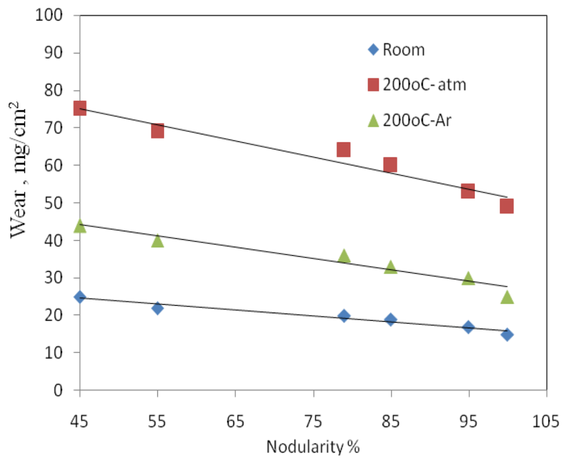

Fig. 10 Effect of nodularity% on the wear of the produced SGI specimens at different elevated temperatures and atmospheres.

Also, Fig. 11 shows the relation between the pearlite% and wear in the produced SGI, from this Figure, it is clear to observe that the wear is decreased slightly with increasing pearlite amount%. This is due to increase hardness of pearlitic matrix. While at same pearlite%, the wear amount is increased with increasing temperature in normal atmosphere, but with Ar atmosphere, the wear is a little decreased at same temperature and pearlite%, because in presence of Ar the chance for oxidation is might be decreased than in presence of normal atmosphere [20]. The Wear amount, mg/cm^2 was correlated as a function of pearlite% (P) at different temperatures and atmospheres in the produced SGI as follow:

At room temperature: Wear amount, mg/cm^2 = -0.115 P + 21.72

At 200^{o}C and air: Wear amount, mg/cm^2 = -0.184 P + 38.70

At 200°C and Argon: Wear amount, mg/cm^2 = - 0.254 P + 67.26
0.015%<P<0.035%

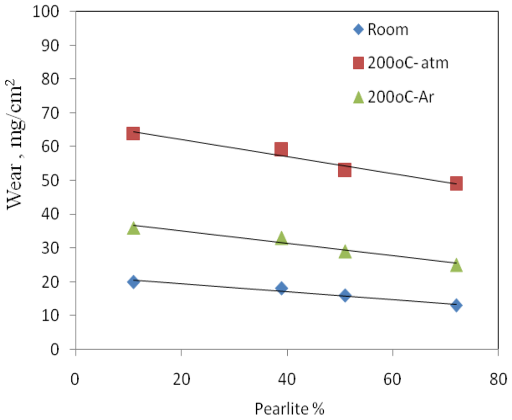

Fig. 11 Effect of Pearlite% on the wear amount of the produced SGI specimens at different elevated temperatures

The wear debris collected from the as-cast SGI is a dark gray color. The wear was carried out using pin-on-disk 0.2m/s for 4000 m and load 47.2 N at different nodularity; 45, 55, 78, 85, 95 and 100%. The size of most debris is ranged from 2 to 40 □ m. The average particles size of wear debris is decreased with increasing nodularity as shown in Fig. 12a-d. The volume, size, morphology and concentration of the wear debris particles produced are likely to depend on tribological factors such as the properties of the material and the loads and movements experienced at the contact surfaces.

IV. Conclusions

The method used for producing ductile cast iron was described. The optimum chemical compositions for producing ductile cast iron are summarized as: CE (4.2-4.5%), Carbon (3.3-3.7%), Silicon (2.1-2.7%) and Magnesium (0.025- 0.035 %). Empirical correlations to calculate the amount of pearlite in the produced SGI based on the Mn%,Cu% and thickness of ingot. The amount of pearlite is increased sharply with increasing Cu and Mn contents but is slightly decreased with increasing the casting thickness. The effect of increasing in Cu % is larger than the effect of increasing in Mn% .Good metallurgical quality will be obtained as the post inoculation increased. The tensile strength and hardness is increased by increasing Mg% and nodularity in the produced SGI.

The wear resistance is increased slightly with increasing of Mg%, nodularity% and pearlite %. At elevated temperature, the wear resistance decreased with increasing temperature in normal atmosphere, but when the Ar atmosphere was used the wear resistance was increased at the same elevated temperature, nodularity and pearlite %.

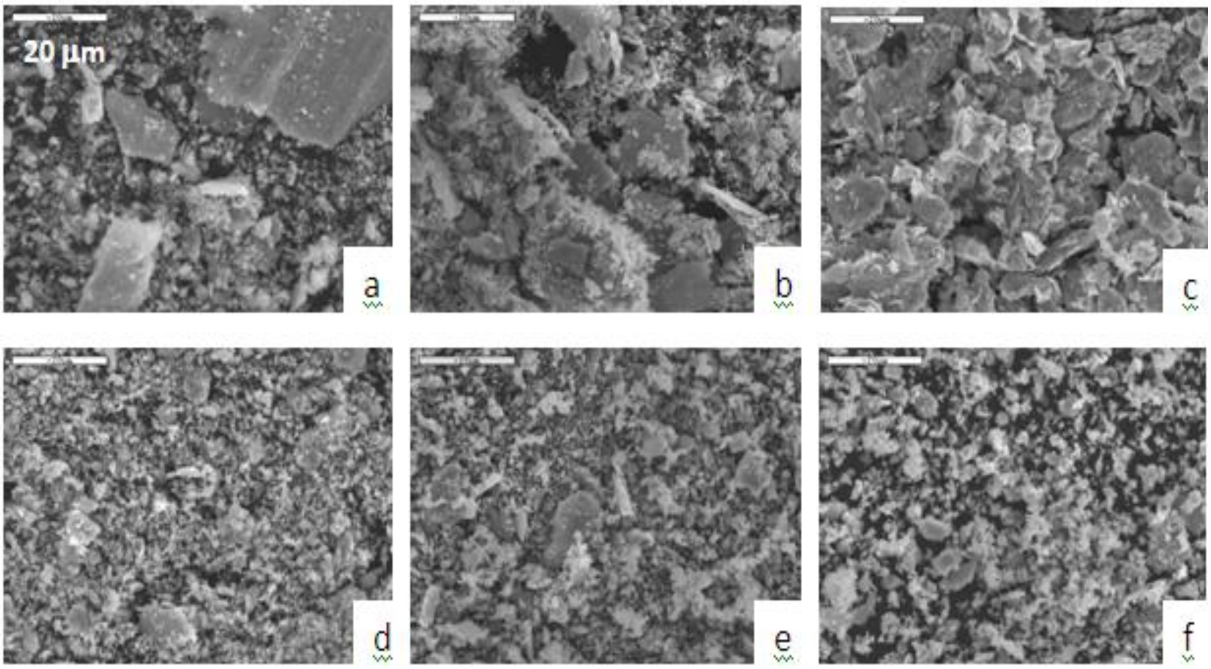

Fig. 12 SEM wear debris for SGI specimens at room temperature and different nodularity %, a) 45% b) 55% c) 78% d) 85% e) 95% and f) 100%.

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