

# **Mechanical Properties of Heat-treated (Full Annealing) Compacted Graphite Cast Iron (CGI) of Varying Microstructures Suitable for Automotives Application**

## **Abstract:**

The work was carried out to determine the mechanical properties of heat-treated (full annealing) compacted graphite cast irons (CGI) of different microstructures suitable for automotive applications. Six types of CGI were selected from numerous available samples based on their chemical compositions. The six CGI were tagged A1, A2, A3, A4, A5, and A6. Full annealing heat-treated was carried out on A1-A6, they were austenized at 920° C, held them at this temperature for 40 minutes, and cooled slowly in the furnace to room temperature. Chemical analysis and carbon equivalent were done, and the results showed that A1-A6 were hypereutectic CGI with different alloying elements ranging from copper, titanium, aluminum, chromium, and nickel. SEM analysis was equally carried out on A1 to A6. The result from the microstructural analysis indicated that A1 and A2 have structures close to gray cast iron, A3 and A4 have a pure CGI microstructure, and A5 and A6 have structures close to ductile cast iron. Mechanical properties (hardness, impact, and wear resistance) were tested on A1-A6. A1 with 209 Brinell hardness number (HBN) has the highest hardness value and A6 with 112HBN has the least hardness number. Similarly, the result from ultimate tensile strength (UTS) shows that A5 has the highest UTS value of 140 megapascal (MPa) and A2 has the lowest value with 38MPa. 38.8J for A1 is the highest impact energy recorded for the series. Lastly, 67% recorded for A6 was the highest wear loss for the series. A1-A6 is suitable for the production of automotive parts especially exhaust system parts and engine blocks.

**Keywords:** full annealing, mechanical property, compacted graphite cast irons, microstructures, automotive

## **1 Introduction:**

Cast iron is an alloy of iron and carbon with carbon content generally between 2% and 4.5 [1]. It contains silicon which is an important ingredient, manganese, phosphorus, and sulfur [2]. Cast iron differs widely in composition and properties. Normal grades of cast iron are not particularly strong and are quite brittle [3]. A new brand of cast iron that will mitigate the disadvantages of normal cast iron is the compacted graphite cast iron (CGI). It has a carbon content between 3.1 and 4.0% and silicon content of 1.7 and 3.0% [4].

This type of cast iron has graphite particles shaped like a cross between ductile iron, which has graphite in a sphere, and regular gray iron flakes [5]. The physical characteristics of the worm-like compacted graphite shape are similar to the best qualities of ductile and grey irons [6].

Since the 1940s, compacted graphite iron (CGI), also known as vermicular graphite iron, has been the most recent addition to the cast iron family [7]. Because vermicular, or worm-shaped, graphite is typically stubby and has blunt edges, CGI has a nice mix of mechanical and physical qualities that lie between ductile and gray cast iron.[8]. Compacted graphite cast iron also has excellent tensile strength, good fracture toughness, and solid impact properties [9]. In addition, it has a high thermal conductivity and better resistance to thermal shock in engineering firms [10]. Compared to ductile cast iron, CGI has greater thermal conductivity, easier casting, and greater strength and stiffness) [11]. Because of its distinct resistance to thermal fatigue, it is very appropriate for use in internal combustion engines and braking components, among other uses [12].

When compared to metals like steel and gray cast iron, CGI is lighter and less expensive [13]. The car industry's growing need for cast lightweight materials like aluminum and metal-matrix composites has fueled the development of novel or more effective manufacturing processes and procedures [14]. Cast iron's low cost of manufacture has kept it competitive even with all the energy used in creating those new lightweight alloys [15].

Most of the mechanical properties of cast irons and their alloys depend on their microstructure[16]. They can be changed by varying the microconstituents in the metal through a heat-treatment process (Sharma and Goel, 2015). Full annealing of compacted graphite cast irons (CGI) is a heat treatment process designed to refine the microstructure, reduce hardness, increase ductility, and improve machinability [18]. It involves utilizing a hypereutectic CGI slowly to a temperature of 920° C and cooling in the furnace to produce ferritic microstructures [19].

Compacted graphite cast irons (CGI) are known for their excellent combination of strength, thermal conductivity, and resistance to thermal fatigue, making them suitable for a variety of demanding applications [20]. In the automobile industry, its higher strength and stiffness compared to gray cast iron, with better thermal conductivity and fatigue resistance than ductile iron makes it an excellent material for the production of engine blocks, cylinder heads, exhaust system parts [21]. It also finds a variety of applications in the production of wind turbines, and turbine housing, and in industries like marine, railroads, agricultural equipment, heavy machinery, and construction equipment [22].

## **2 EXPERIMENTAL PROCEDURES**

Six compacted graphite cast iron was taken to the laboratory to determine their chemical compositions and they were heat treated in the furnace. After, the heat-treated process, mechanical tests were carried out on the six samples terms A1, A2, A3, A4, A5, and A6.

## 2.1 Determination of the Composition Analysis of CGI

Skyray EDX 3600B energy dispersive X-ray fluorescence spectrometer was used to determine the elemental composition of six different CGI before full annealing was carried out in the furnace. X-ray fluorescence is a powerful technique used in a wide variety of elemental composition of various materials[23]. XRF analyzers are widely recognized as a means for accurate, rapid and non-destructive testing[24]. The skyray EDX3600B is a high-end energy dispersive spectrometer with a large sample chamber which support most sample size(Folorunso and Bello, 2021).

## 2.2 Full Annealing Heat Treatment

Full annealing was done on samples 1 to 6 using a muffle furnace. This compacted graphite cast iron produced was austenized at 920 °, holding it for 45 minutes and cool slowly in the furnace. The resulted austenized materials produce from this process which is ductile in nature is labelled A1, A2, A3, A4, A5 and A6.

## 2.3 Carbon equivalent of the Heat-Treated CGI

The carbon equivalent of the CGI produces will be calculated using equation 1(Gregorutti and Grau, 2014).

$$CE = C + (Mn + Si)/6 + (Cu + Ni)/15 + (V + Mo + Cr)/5 \quad (1)$$

Where CE is carbon equivalent, C is % by weight of carbon, Mn is % by weight of manganese, Si is the % by weight of silicon, Cu is the % by weight of copper, Ni is the % by weight of nickel, V is the % by weight of vanadium, Mo is the % by weight of molybdenum, Cr is the % by weight of chromium that is present in CGI.

## 2.4 Microstructural Examination

### 2.4.1 SEM analysis

microscopy (SEM) was carried out using a carl Zeiss sigma field Emission gun scanning electron microscope under 1000 magnification of 10µm, with energy dispersive spectrometer (EDS Scanning electron) these was done to examine the internal structures of the CGI produced to determine their degree of graphite growth and nodularity[27].

### 2.5.1 Hardness test

The hardness test was conducted using the hand-held Brinell tester. This conforms to ISO and ASTM E03-18 [28] standard which was used on all metals and alloys on any sample size[29]. The set of tests were performed on A1-A6, the test was done on four occasion and the average was recorded.

### 2.5.2 Tensile tests

Tensile tests were performed on the six samples of CGI produce labelled A1-A6 using universal testing machine. Material testing system with load capacity of 50 KN, and at loading speed of 10 rpm and maximum chuck diameter 10mm. The tests samples were prepared on the lathe machine to cylindrical shapes of 9 mm x 16 mm. The samples were inserted into the chuck and was close by align key to grip them and the samples were pull apart until they broke into pieces.

### 2.5.3 Impact strength

Impact strength was evaluated on the heat-treated samples labelled A1, A2, A3, A4, A5, and A6. The test was conducted using ASTM standard of dimension 9 mm x 16mm using the Hounsfield balance impact machine. The V-notch impact specimen was clamp into the pendulum chuck and locked with align key, the notched side facing the striking edge direction. The pendulum was released at a velocity of 4 m/s with maximum energy of 170 these were done to fracture the materials and the energy absorb by the materials were noted and recorded. Four tests were carried out on each specimen and their average were recorded in joules which is unit of energy[30].

### 2.5.4 Wear test

The wear test of samples was carried out according to ASTM G99.15. The step on disc rolling dry wear method was use which was carried out using a Rolling Sliding wear tester. The initial mass  $M_1$  of samples were recorded before allowing them to be in contact with a rolling disc for one minute at 20 cycles. The final mass  $M_2$  of the samples were also recorded. The wear index  $R$  was obtained by Equation (2) ( Dongo *et al.*, 2022).

$$R = \frac{M_1 - M_2}{RPM} \times 100\% \quad (2)$$

Where  $M_1$  is initial mass (g),  $M_2$  is final mass (g) and  $RPM = 20$ .

### 3 Results and Discussion.

#### 3.1 Elemental analysis of the Heat-Treated CGI (A1-A6)

Based on the theoretical failure analysis and chemical compositions of some selected silencers, the following CGI were obtained with varying alloying elements, tagged A1, A2, A3, A4, A5, and A6. Results from chemical composition analysis in Table 1, shown that CGIs obtained were hypereutectic irons with 4.35% carbon with the presence of Cu, and Cr which aids the increase of the pearlite phase so as to increase the hardness, heat resistance and strength which is in agreement with Ning *et al.*, 2023). These is shown in A1 and A2. Al, Ni and Si found in A4 and A5 were obtained purposely so as to aid graphitization which promote ferritic phase and aid ductility in accordance with Boulifa and Hadji, 2021). In addition, Ni and Cr also increase thermal conductivity but it shown a deleterious effect on percentage elongation, UTS and toughness as seen in A3 and A6 according to [33].

**Table 1:** Summary Elemental Composition of the Heat-Treated CGI Materials (A1-A6)

	Fe	C	Si	Cu	Cr	Ti	AL	Ni	Mg	S	Mn
A1	93.1000	4.3500	1.5400	0.1510	0.0773	0.0067	0.2090	0.0466	0.0025	0.0953	0.216
A2	92.6000	4.3500	1.8200	0.1820	0.0900	0.0134	0.1610	0.0438	0.0064	0.1390	0.2800
A3	92.5000	4.3500	1.8800	0.1820	0.0943	0.0211	0.1620	0.0433	0.0038	0.1350	0.2590
A4	92.4000	4.3500	2.0000	0.3150	0.1310	0.0183	0.0307	0.0531	0.0048	0.1320	0.2770
A5	92.0000	4.3500	2.2300	0.3290	0.1450	0.017	0.0597	0.1790	0.0081	0.1440	0.2820
A6	92.4000	4.3500	2.0200	0.3400	0.1200	0.0374	0.0294	0.0053	0.0053	0.1200	0.2760

#### 3.2. Carbon equivalent of the Heat-Treated CGI Materials (A1-A6)

The carbon equivalent (CE) of the CGI is shown in Table 2. All the CGI from A1-A6 are in excellent condition and fall into the range of CE of CGI which should be greater than 4.35 which is in line with (Medyński and Janus, 2018).

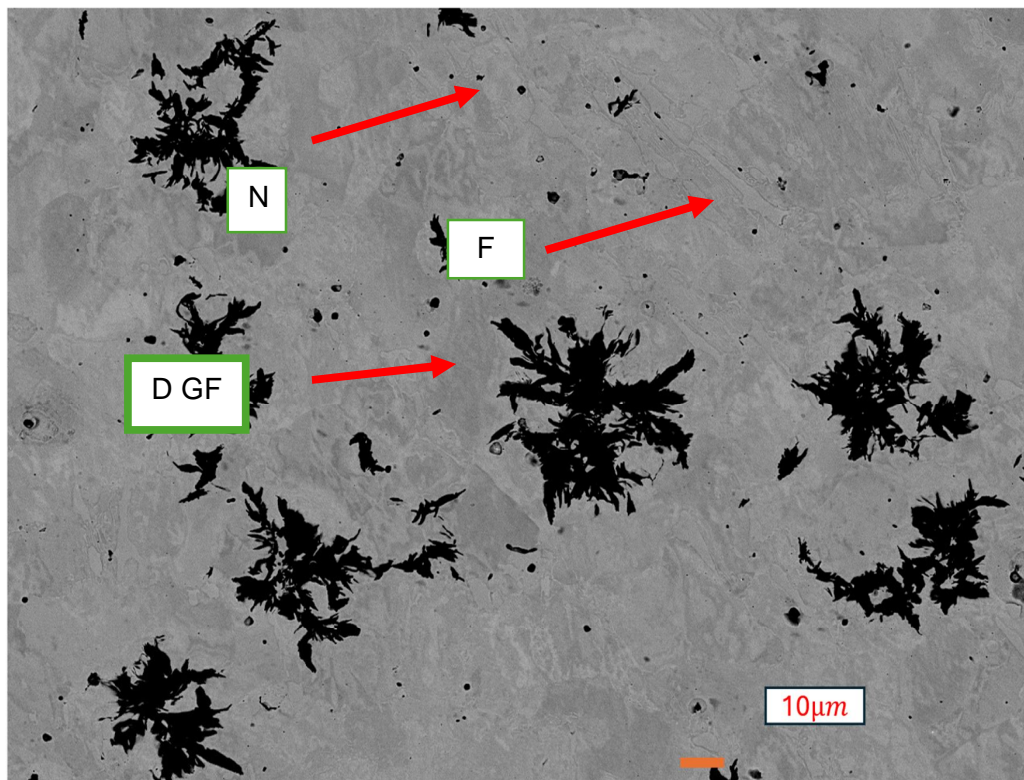
**Table 2:** Carbon equivalent of the Heat-Treated CGI Materials (A1-A6)

SN	C1	C2	C3	C4	C5	C6

CE	4.65	4.85	4.96	4.78	4.83	4.79
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### 3.3 SEM Analysis of A1-A6

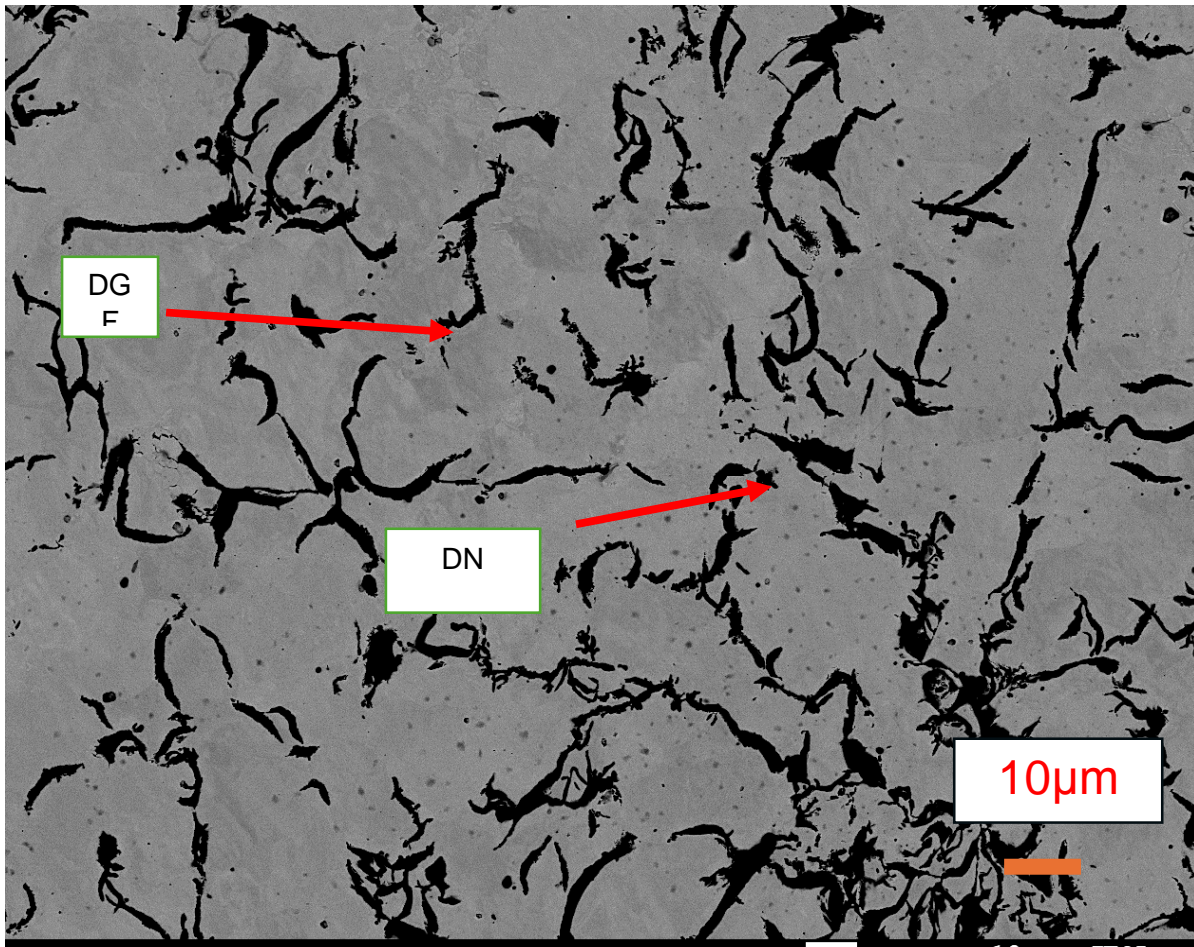
Plate1 shown a CGI with a distorted clusters graphite flakes (DGF) in ferrite under 1000 magnification. The microstructure of A1 is close to gray cast iron with little percentage of nodules in the ferrite phase



**DGF= Distorted graphite flakes in ferrite, F= ferrite, N= nodules**

**Plate 1: A1 SEM image**

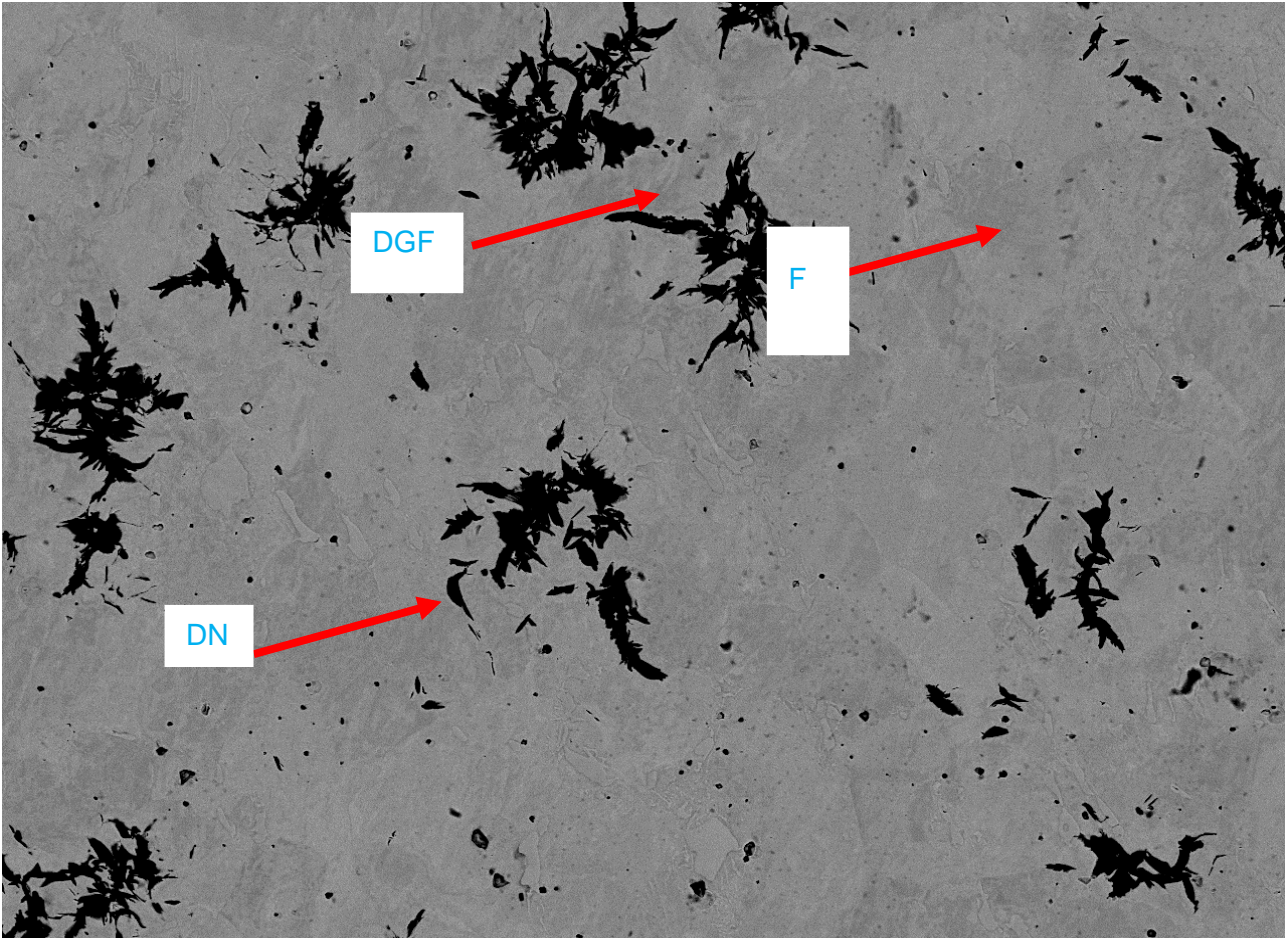
Plate2 shown several distorted graphite flakes (DGF) in ferrite under 1000 magnification. The microstructure of A2 is also close to gray cast iron with little percentage of distorted nodules (DN) in the ferrite phase. The nodules in A2 are more than the one in A1.



**DGF= Distorted graphite flakes in ferrite, F= ferrite, DN= distorted nodules**

**Plate 2: A2 SEM image**

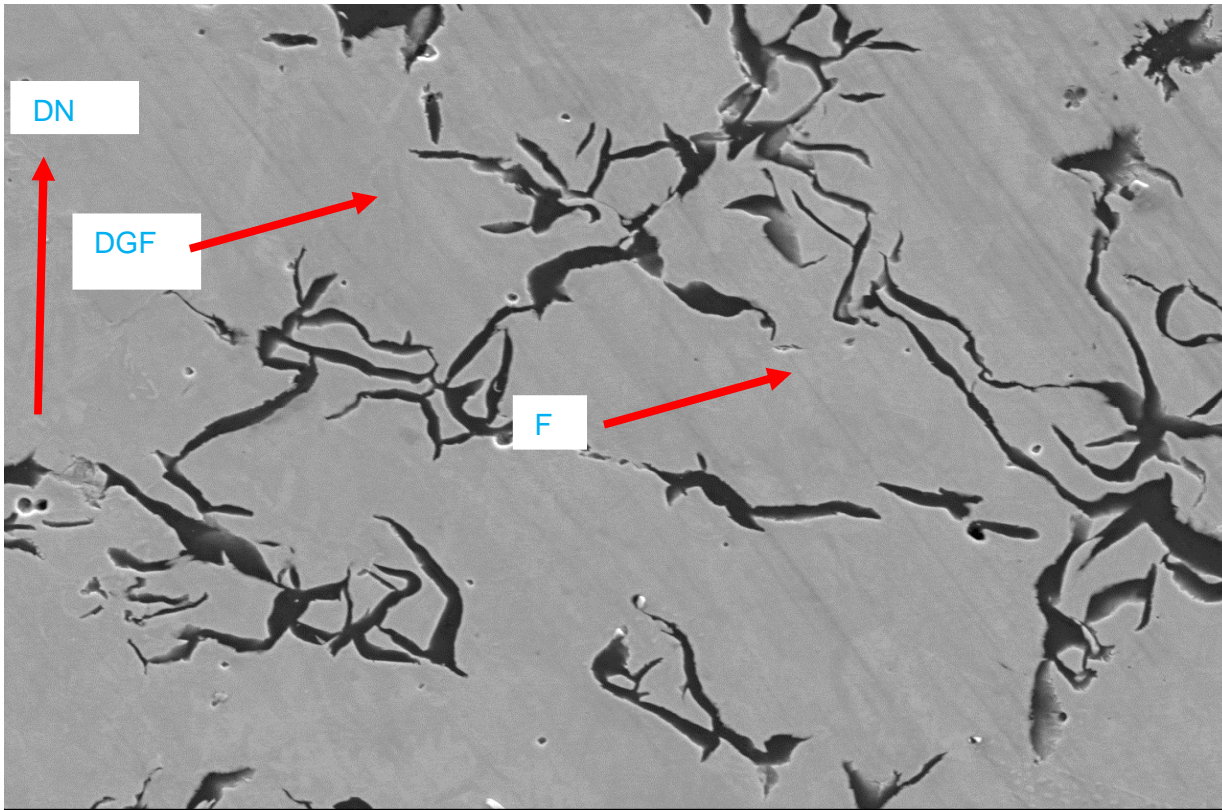
Plate3 shown several distorted graphite flakes (DGF) in ferrite under 1000 magnification. Some of distorted graphite flakes are separated. The microstructure of A3 is pure compacted graphite cast iron with equal number of distorted nodules (DN) in the ferrite phase.



**DGF= Distorted graphite flakes in ferrite, F= ferrite, DN= distorted nodules**

**Plate 3: A3 SEM image**

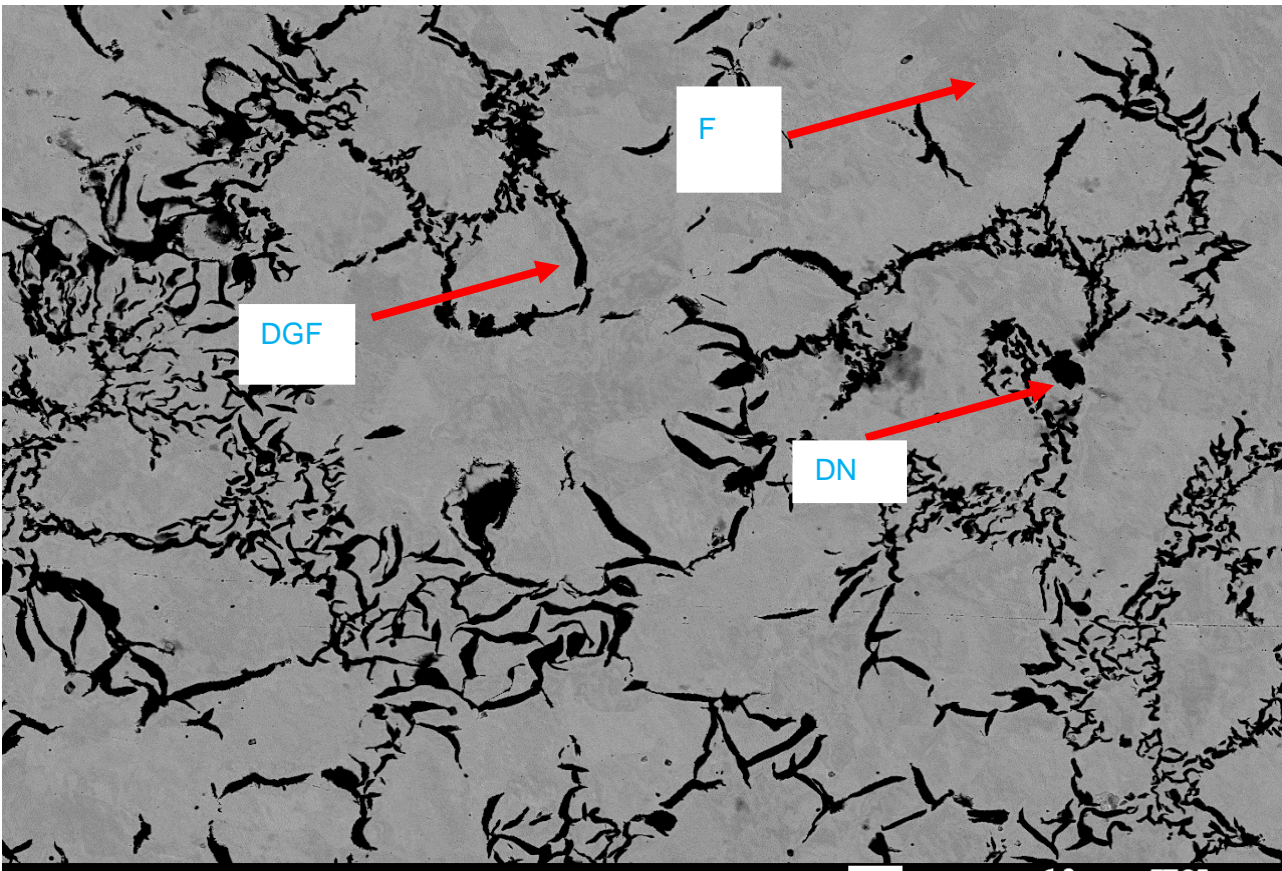
Plate4 shown several distorted graphite flakes (DGF) in ferrite under 1000 magnification. Some of distorted graphite flakes are separated. The microstructure of A4 is also a pure compacted graphite cast iron with equal number of distorted nodules (DN) in the ferrite phase. The nodules in A4 are smaller in sizes than the nodules in A3 because of the percentage of Cu which served as nodules reducer (anti-nodularizers) in accordance with. [35].



**DGF= Distorted graphite flakes in ferrite, F= ferrite, DN= distorted nodules**

**Plate 4: A4 SEM image**

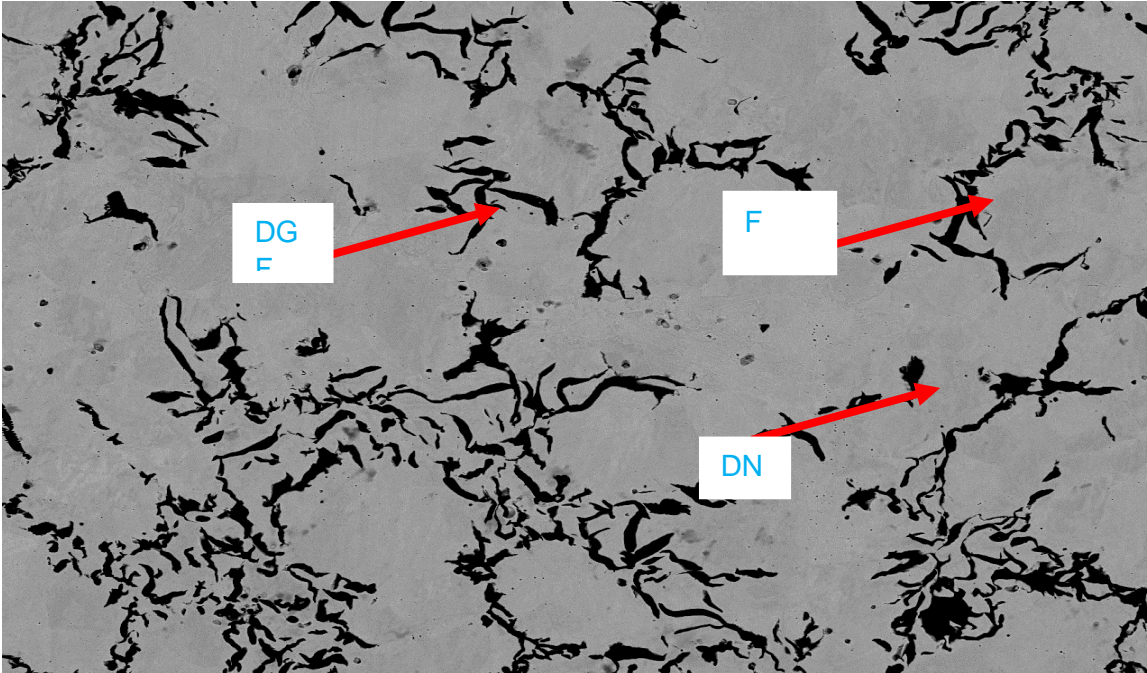
Plate5 shown several heavily distorted graphite flakes (DGF) in ferrite under 1000 magnification. Some of distorted graphite flakes are separated. The microstructure of A5 is more of ductile cast iron with some distorted nodules (DN) in the ferrite phase. The nodules in A5 are bigger in sizes than the nodules in A1 to A4 because of the percentage of silicon, magnesium which served as nodules enhancers which agrees with [4].



**DGF= Distorted graphite flakes in ferrite, F= ferrite, DN= distorted nodules**

**Plate 5: A5 SEM image**

Plate6 shown several heavily distorted graphite flakes (DGF) in ferrite under 1000 magnification. Some of distorted graphite flakes are separated. The microstructure of A6 is mor ofductile cast iron with some distortednodules (DN) in the ferrite phase. The nodules in A6 are also bigger in sizes than the nodules in A1 to A4 because of the percentage of silicon which served as nodules enhancer and copper which increase pearlitic phase. which agrees with [36].

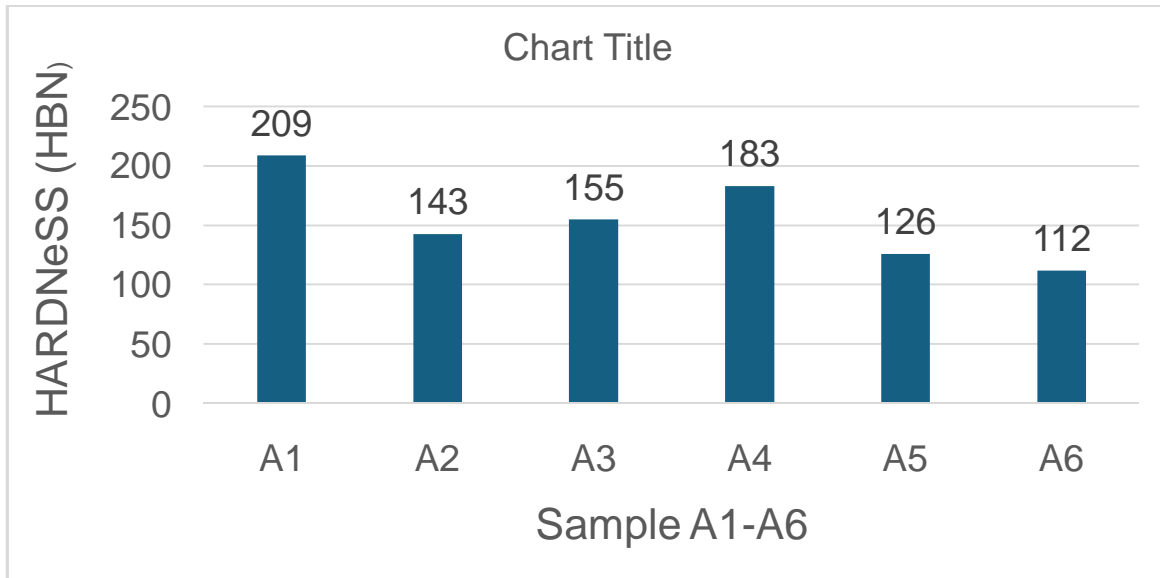


**Plate 6** DG= Distorted graphite flakes in ferrite, F= ferrite, DN= distorted nodules

**Plate 6:** A6 SEM image

#### 4.4.1 Hardness

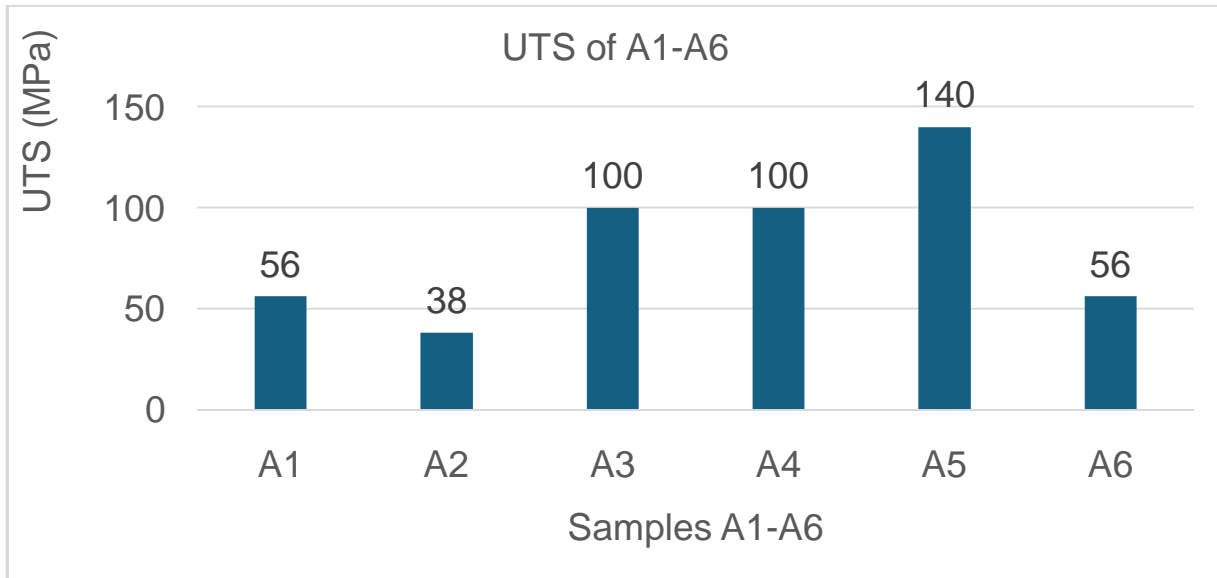
The hardness results of A1 to A6 from figure 1 reveals, that the materials are tough, ductile and have some elements of plastic deformation before failure. These conditions are desirable as they give a warning before failures in accordance with (Elena et al, 2020). Also, A1 has the highest Brinell hardness (HB) value of 209 because its structure is close to gray iron microstructure, followed by sample A4 with 183HB this is due to the high percentage of Cu, Cr, and Mn which increase the hardness of CGI in accordance with [38]. The lowest being sample A6 with 112HB values because it's a ductile cast iron and ductile cast iron has the least hardness value in comparison to gray and compacted graphite cast iron which is in line with [39]. Summarily, all the samples' microstructures are mostly ferritic in nature with a little blend of pearlite except for A1 and A2 that have a higher pearlite phase which is responsible for their high hardnesses [40].



**Figure 1:** Variation of Hardness heat-treated samples A1-A6

#### 4.4.2 Tensile Test

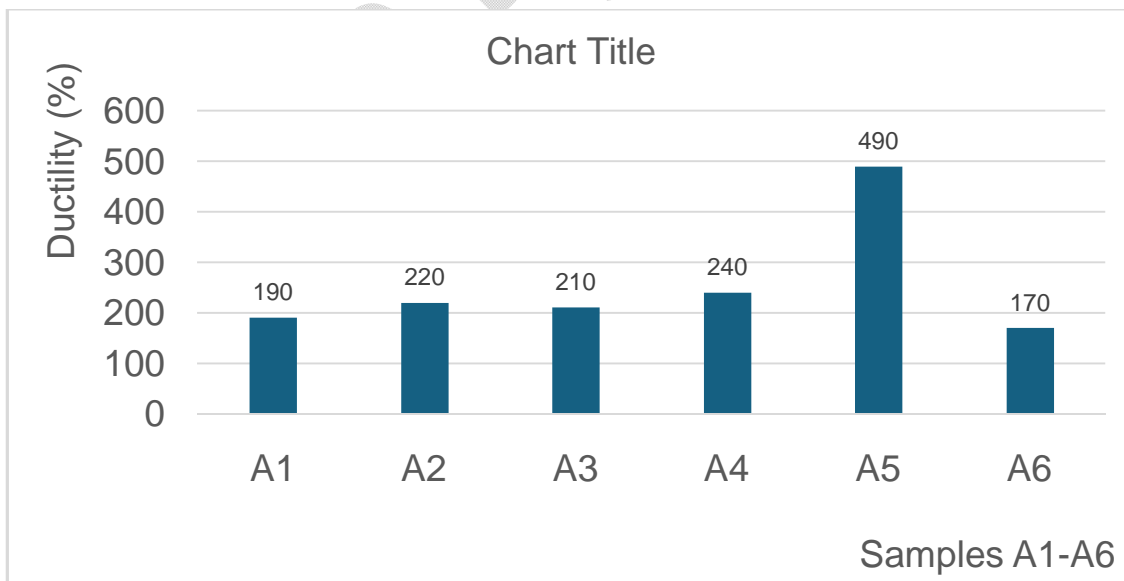
The tensile test results for the CGI-heat-treated samples A1-A6 are shown in Figure 2. The following was deduced from the graph. A5 has the highest ultimate tensile strength (UTS) value of 140 megapascals (MPa) and A2 has the lowest UTS value of 38 MPa. A1 and A6 have UTS values of 58 MPa, and A3 and A4 have 100 MPa, respectively. The highest UTS of 140 MPa for A5 in the series is in agreement with [41]. That states that the UTS value of ductile iron is higher than that of gray cast iron due to alloying elements like magnesium, aluminum, and chromium additions. These elements promote ferritic microstructure over pearlite, and this is responsible for the H5 value.



**Figure 2:** Variation of UTS for Samples A1-A6

#### 4.4.3 Ductility Test

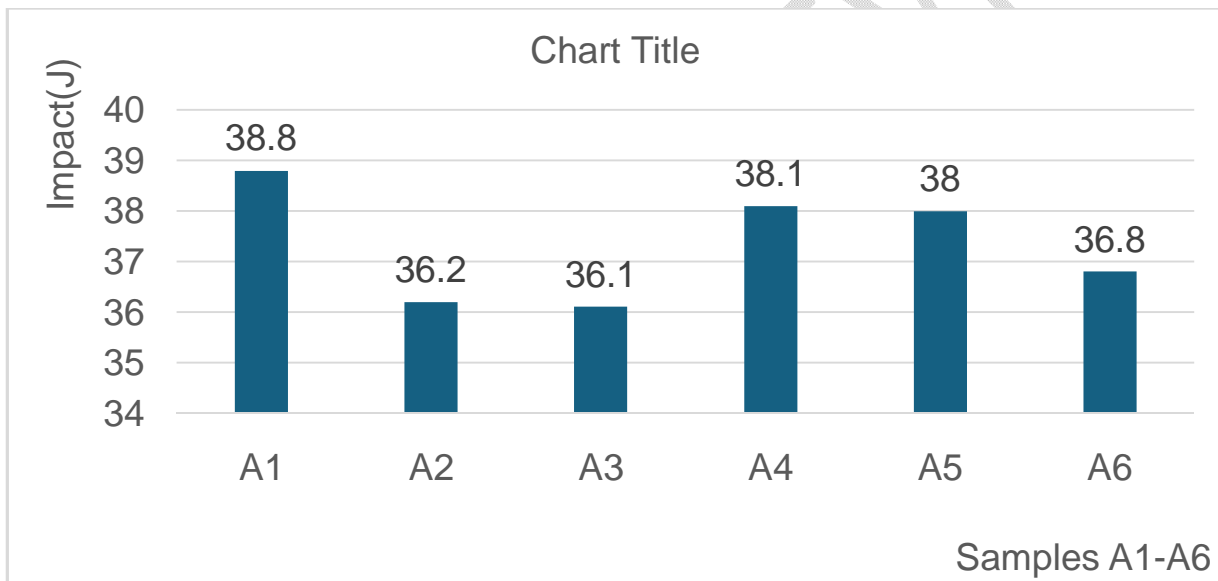
From Figure 3, it can be deduced that A5 has the highest ductility of 490 % due to the presence of magnesium as an alloying element that aids the transformations of  $\alpha$ -ferritic microstructure over the pearlite phase which is in line with [42] and it is expected that ductile cast iron should have ductility close to that of steel according to Ikeda *et al.*, 2019 .



**Figure 3:** Variation of Ductility with Samples A1-A6

#### 4.4.4 Impact strength

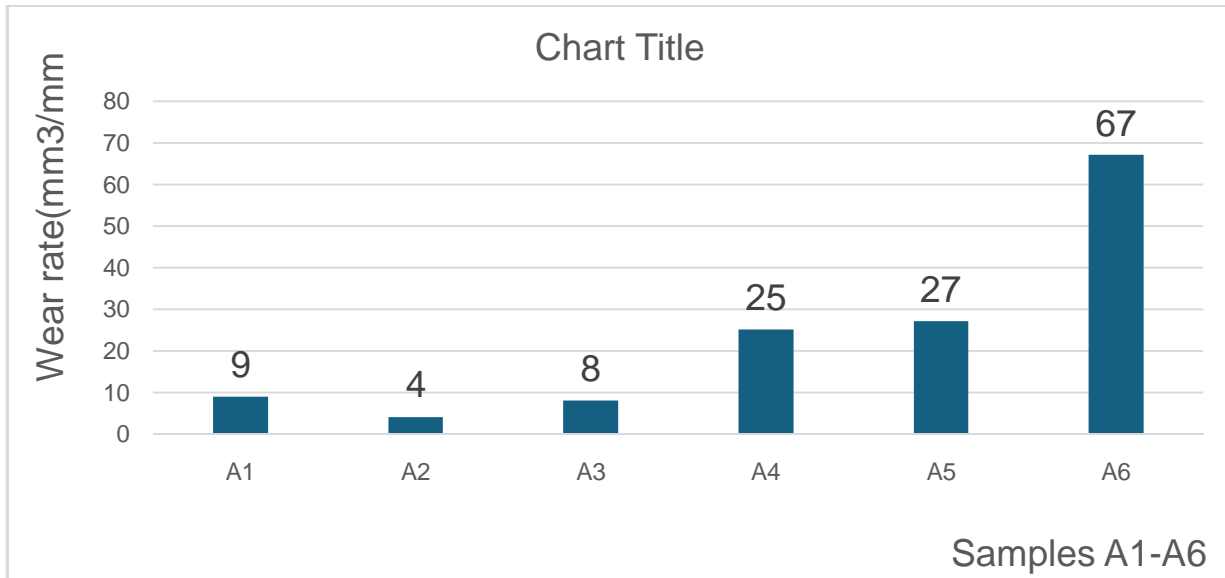
The result from Figure 4, shows that A1 has the highest impact energy of 38.76 J/mm<sup>2</sup> in the series. This is normal because of surface hardening and the presence of copper and silicon in line with [44]. However, the differences in the impact energy are not much from A1 to A6. It can be seen clearly that the differences in A3, A4, and A6 are not that much because of the little variance in the pearlitic and ferritic phases. These sets of series are ideal and suitable for exhaust system outer body parts production according to (Kucharska and Moraczyński, 2020)



**Figure 4:** Variation of Impact test with Samples A1-A6

#### Wear

Figure 5 reveals, that A6 has the highest material loss with wear resistance of 66% for the series. The least material loss was A2 and A3 because they are gray cast iron with copper addition and because pearlite microstructure phase is more predominantly present than the ferritic phase which conforms with [46]



**Figure 5:** Variation of Wear Rate of Samples A1-A6

#### Conclusion

Six samples of varying CGI microstructures were heat-treated, and they were tagged A1, A2, A3, A4, A5, and A6 respectively.

The carbon equivalent was calculated, and it indicates that they were hypereutectic cast irons.

Results from the SEM analysis indicated that A1 and A2 have a microstructure close to that of gray cast irons because of higher percentages of distorted graphite flakes (DGF), and A3 and A4 were compacted graphite cast iron (CGI), and A5 and A6 have structure close to ductile cast irons.

The mechanical properties of A1-A6 follow the trend of properties of gray, CGI, and ductile cast iron respectively in that order except where alloying elements and microstructure were employed to change the property i.e. the hardness value of A4 and A3 which were higher than that of A2 because of addition of alloying elements that were cementite and pearlite stabilizers.

Also, the trend follows in the UTS and ductility results except for A6 which has its values close to the A1 due to high percentages of copper and chromium as an alloying element which promotes pearlite phase.

In addition, the impact energy of gray cast iron was expected to be higher than that of CGI and ductile cast iron. A1 with 38.8J has the highest impact energy in the samples because it has its microstructure close to gray irons and A3 has the least impact energy with 36.1J because its alloying element promotes ferrite phases. Lastly, the wear rate of 67% and 27% of A6 and A5 were the highest in the series because they are ductile cast iron.

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