Evaluation of Structure - Properties Interdependence of Commercial Grey Iron in Silica & Slag Moulds

O.R. Oloyede, S.A. Afolalu, O.J. Adelakun, A.A. Abioye, A.O.M. Adeoye.

Abstract – **This study present the effect of cooling rate of basic foundry moulds on the microstructure and mechanical properties of graphitic cast iron. Commercial grey iron has the highest volume tonnage output beside steel in the foundry industries worldwide. Hence, its rate of production depends largely on its moulding time. As a result of this, moulds selection is essential in its production and property. Silica and Ferro chrome (Fe-Cr) industrial slag are 2 common mould materials used in foundry for casting especially grey iron using Sodium-Silicate-Carbondioxide process. Three moulds were produced, one from each of these moulding materials and the third from percentage mixture of the two moulding materials. Cast samples were obtained using scraps of commercial grey cast iron BS1452 GRADE 250. It was melted and cast using the 3 moulds. Analysis shows that Fe-Cr slag mould exhibited highest cooling rates followed by mixed materials mould and lastly the silica mould. The structural analysis of the as-cast samples from each moulds type reveals the Fe-Cr slag mould cast has the finest uniformly distributed graphite flakes with average string lengths of 63.12, 38.62, and 26.18 µm and corresponding observed toughness of 84-89 HRC, 74-78 HRC, 72-74 HRC for the slag mould cast sample, slag-sand mixed mould cast sample and silica mould cast sample respectively. Consequently, there is relative increase in the samples hardness values with increasing cooling rate.**

Index Terms – **Grey iron, Moulding sand, Fe-Cr Slag,SEM**

I. INTRODUCTION

Sand mould casting is the commonest process in foundry industry due its wide range of applications in making big cast sample sizes, it is flexibility and can be used to produce any mould size.It is efficient, cost effective and can be easily monitored. Currently, the benefits provided by sand castings in the metallurgical industry in large production rate which is the reason for its popularity world over. Cast iron is one engineering materials that is synonymous with casting. However, slag for mould making is currently in vogue as a result ofits desire properties such smoother surface finishing and betterthermal conductivity.

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S.A. Afolalu is a researcher and a seasoned lecturer in Department of Mechanical Engineering, Covenant University, Ota, Ogun State, Nigeria. Sunday.afolalu@covenantuniversity.edu.ng, +2348035785758

O. R. Oloyede is a Senior Lecturer, Researcher and a Consultant in the Mechanical& Mechatronics Engineering Department, College of Engineering, AfeBabalola University, Ado-Ekiti, Ekiti State, Nigeria.
[Tel: +2348037262500; engrlekanoloyede@yahoo.com].

A. O. M. Adeoye, P. O. Aiyedun andA. A. Aderoba are Professors in Mechanical & Mechatronics Department, College of Engineering. Afe Babalola University, Ado-Ekiti, Ekitit State, Nigeria.

O. J. Adelanakun and A. A. Abioye are equally lecturers and member of Mechanical Engineering Research team in Covenant University.

Research on slag usage are being explored in many foundry shops and this study, we will be outlining one of such foundry shop solid wastes (slags) and fly-ash to replace the green sand i.e. pure silica that has being in use for ages [1]. Meanwhile, very limited work has been reported on using slags for mould making. The reason being that, it is essential to conduct thorough investigation into a material that will substitute for the existing natural sand that is being used in high demand in various foundry shops [2]. Hence, efforts is being made to convert various by-products or wastes generated in foundry industry to mould making. Therefore, this study is to show case the usefulness of often wasted Ferro chrome (Fe-Cr) slag materialfor mould making in foundry shops as a better substitute for Silica [3]. Fe-Cr slag has for long been classified as industrial solid waste generate from the Ferro alloys plants. Globally, the iron smelting companies generates about 6.5 to 9.5 million tons Fe-Cr slag per annum and this is likely to be increased by 2.8 to 3% by year 2025. However, it has been discovered that the chemical and physical properties ofFe-Cr slag and that ofSilica are similar. Slag is readily available as industrial solid waste in large quantities[4]. We are hereby exploring a comparative effect of the rate of cooling of this moulding material to that of green sand relative to the microstructure and mechanical properties of the as-cast itemsmoulded using this materials moulds [5].

II. METHODOLOGY

The mould materials used in this study were highly refined silica sand and processed Carbon Ferro Chrome (Fe-Cr) slag. The cast Iron bar was obtained from Overseas Aluminum Plants (OSA), India. The moulds were made with strict adherence to ASME foundry specification using sodium silicate along with CO_2 gassing to avoid porosity in the as-cast samples. Three (3) different moulds were prepared; (1) with 100% Silica, (2) with 100% Fe-Cr slag and (3) Mixture of 60% Fe-Cr slag and 40% Silica. Each of the mould was prepared without contaminations [6]. Thereafter, the cast iron was melted and the molten metal was poured into the each mould made from Silica, Fe-Cr slag and mixedmaterial. The moulds have similar cavities pattern and good gate system for even distribution and easy solidification [7]. The moulds temperature were monitored using RF thermocouples. Other factors such as pouring time was kept constant since the mould dimensions were the same for each of the mould. The cooling was monitored and recorded consistently and simultaneously for each mould material. After solidification, the as-cast from each mould were taken out from the mould boxes and subjected to microscopic and mechanical properties evaluations. It is assumed at this stage that microhardness is used as measure of the mechanical property of the samples[8].

A. Metallographic Examination

Cast samples from the 3 moulds were cut out and prepared in a standard metallurgical laboratory with strict adherence to AIST manual for intermetallic sample preparation. These were thereafter subjected to optical and SEM microscopy examination using Light Olympia multiple lens and EVO 60 Scanning Electron Microscopes(The SEM has an inbuilt Energy Dispersive Spectroscopy, EDS) to analysis and confirm the elemental composition analysis of the as-cast samples obtained from the 3 mould materials. Nital (2% HNO_3) was used as etchant for thespecimens. ImageJ software was used to analyze the morphology of the various graphite form in the samples. Finally, the values of the mean and standard deviation of the gap were computed for100 counts minimumon thescannedimagesobtained from scanning electron microscope [9].

B. Mechanical Properties Evaluation

The as-cast samples from the 3 mould materials were subjected to microhardness, tensile and impact strengths tests. The hardness values were measured using Rockwell hardness tester with initial load of 10 kgf; and major load of 150 kgf. An average of 15 readings from each of the sample was recorded. Using a typical Universal Electrochemical testing machine, the tensile test samples were prepared in line with its specification and the reading was evaluated at the transverse and longitudinal directions of the samples with the measurement and mean average taken from average of four different diagonals of the specimen. Computer controlled Servo-Hydraulic universal testing machine was used to test for an average of three specimen from each mould at room temperature to obtained an on-line load-elongation sequence. Compression tests were carried out on cylindrical form specimens using height of 16mm to width of 16 mmi.e. H/D=1.0.Traditionally, Notched bar impact tests were carried out as per ASTM-A370 standards. This tests was carried out with Charpy impact test machine and repeated three times to determine the average for each specimen casted so as to give credible values and information about the impact strength of the samples [10].

III. RESULTS AND DISCUSSION

A. Cooling rate from each mould

The cooling rate for each sample from the different mouldswere measured, recorded and plotted (Temperature vs Time) at constant geometry of items and other factors being equal. The mould materials (Silica, Fe-Cr slag and mixed material) have different heat transfer coefficient. This reflected in their different thermal conductivity during solidification of the as-cast items. The thermocouples readings shows clearly that the Fe-Cr slag mould materials dissipate heat faster than the Silica and the mixed mould material. Fig. 1 shows the various cooling temperature against time for each mould sample, which explains why sand seems to be the least among the 3 materials. The location of the thermocouples were uniform and same for each mould. So this again, makes it clear on the purpose of the runner, the riser, and mid-point vetting on each of the mouldreadings as shown in Fig 1(a-c). It then means that the Fe-Cr slag mould emits more heat than bothSilicaand the combination of Silica-Slag moulds.Actually this is in consonance with the readings on the thermocouples located in similar positions of the mould boxes. More temperature reading in Fe-Cr slag mould indicate faster rate of heat emission across the boundary of the system as compared to the other materials [11-13]. In general Fe-Cr slag particles have higher thermal conductivity than the 2 mould materials.Hence, the moulds made with Fe-Cr slag particles exhibit more mould temperatures radiation. Rapid heat loss during solidification contribute greatly tothe revealed fine microstructure which can be re-engineered through morphology modification and made more useful to desired mechanical properties tempering or controlled annealing [12-16].

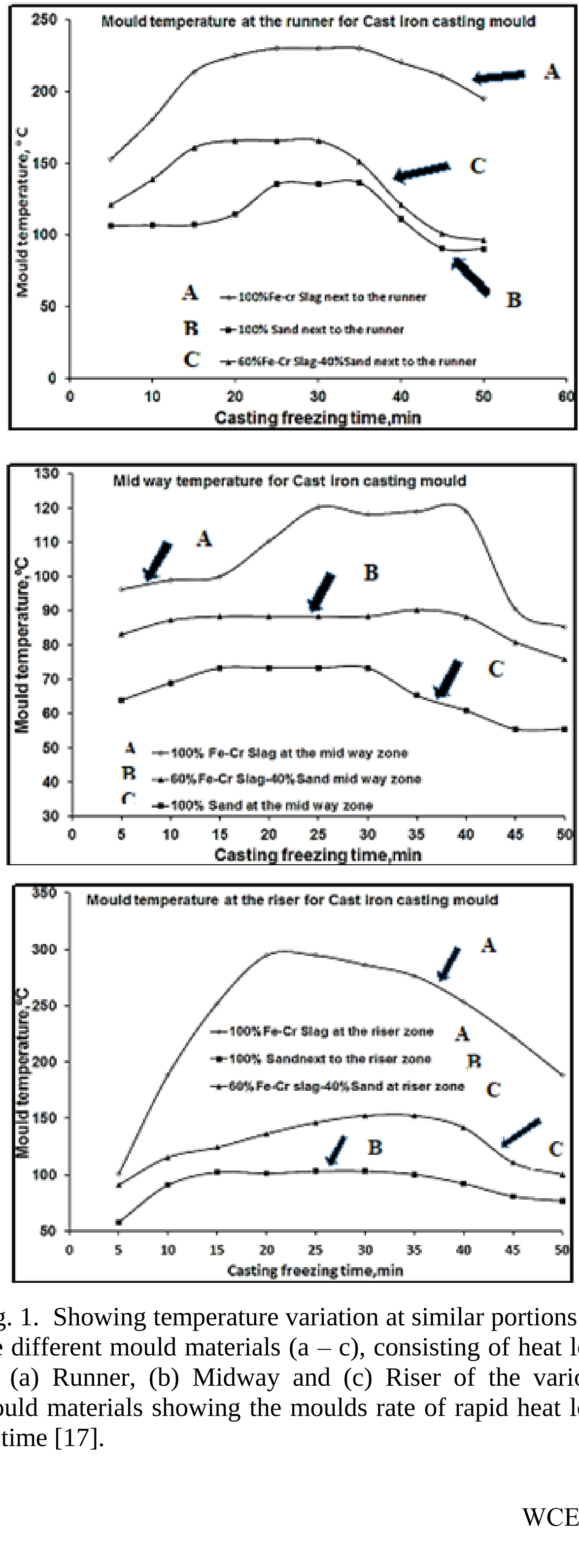

Fig. 1. Showing temperature variation at similar portions on the different mould materials (a – c), consisting of heat loss at: (a) Runner, (b) Midway and (c) Riser of the various mould materials showing the moulds rate of rapid heat loss vs time [17].

B. MicrostructureEvolution and Evaluation

Themicroscopic analysis of the as-castsamples from the 3 moulding materials namely: Silica, Fe-Cr slag and the mixedmaterialare as presented in Fig. 2 (a-c) andFig. 3 (a-c). The elemental composition of the grey cast iron alloy used is as displayed in Table 1 below.This alloy by the reason of its Carbon Equivalent (EC) is said to be hypoeutectic meaning that it lies to the left of the eutectic point on the Fe – C phase diagram. The graphite flake size, shape and type were examined as per the procedure described in EN ISO 945-1994 standards [5]. Graphite – Ferrite microstructure dominates the morphology of this alloy as seen under optical microscope and SEM [18].

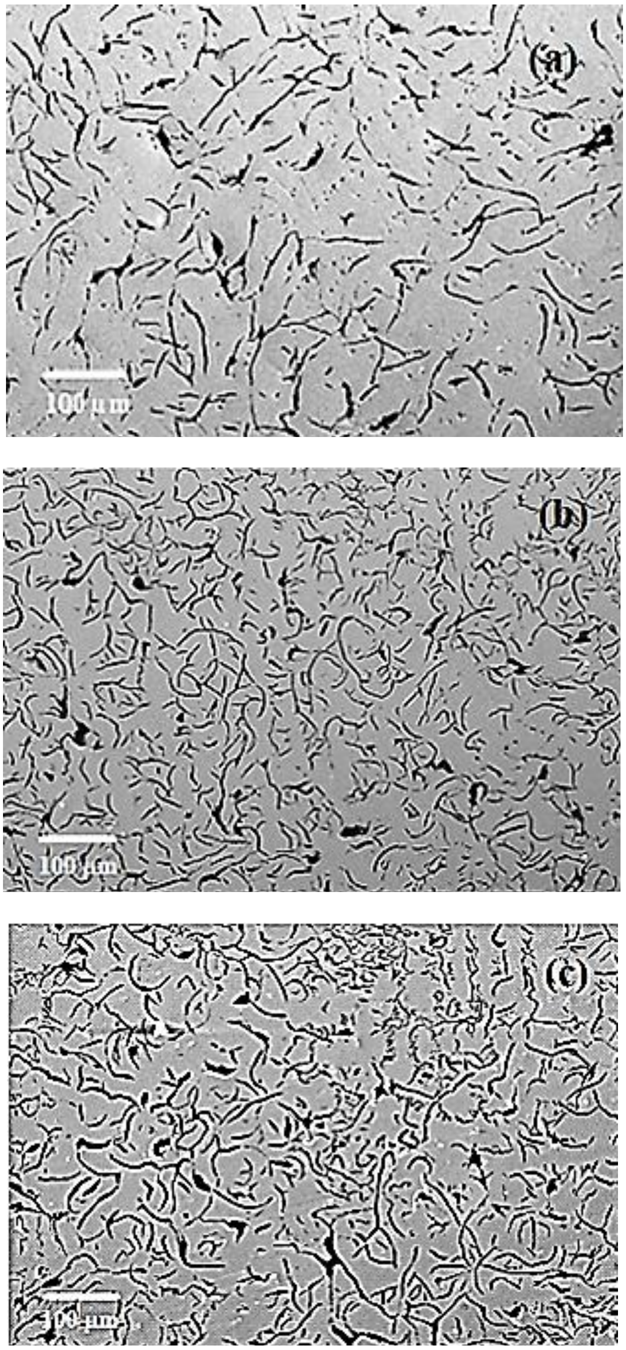

Fig. 2. SEM microstructure of graphite – ferrite of the as-cast grey iron in (a) 100% Silica mould (b) 100% Fe-Cr Slag and (c) 60% Fe-Cr Slag + 40% Sand Mould materials.

The above morphologies is typical of grey cast iron cooled in air i.e. Normalized, Hence, all the cast samples from the 3 moulds show uniform graphite flakes distribution in the iron matrix, thereby confirming the size and type of the cast iron. Meanwhile, the as-cast made from Silica mould shows relatively sharp, long graphite in ferrite matrix as shown in Fig. 2(a). This is more likely to be due to the prevailing slow loss of heat in silica mould which permits more time for graphite segregation. However, according to the EN ISO 945-1994 standards the morphologies of this as-cast from this Silica mould is classified as type-B graphite flakes. Whereas the product of the as-cast made from Fe-Cr slag mould shows very fine and small granular size graphite flake that are uniformly disturbed all through the matrix ferrite matrix as show in Fig. 2(b). The emergence of this fine structure is mainly due to rapid cooling rates in the slag mould compared to that of Silica mould as-cast sample. The Fig. 2(c) shows varied coarse – fine grain microstructure of grey iron which is visibly as a result of combined or mixed texture of the slag and the sand.The displayed morphology is made up of reoccurring form of graphite in discrete flakes been mixed with fine and long flakes that is combined. The rates of cooling in the mixed material mould is somewhere between the Silica and that of Slag moulds [19].The type of

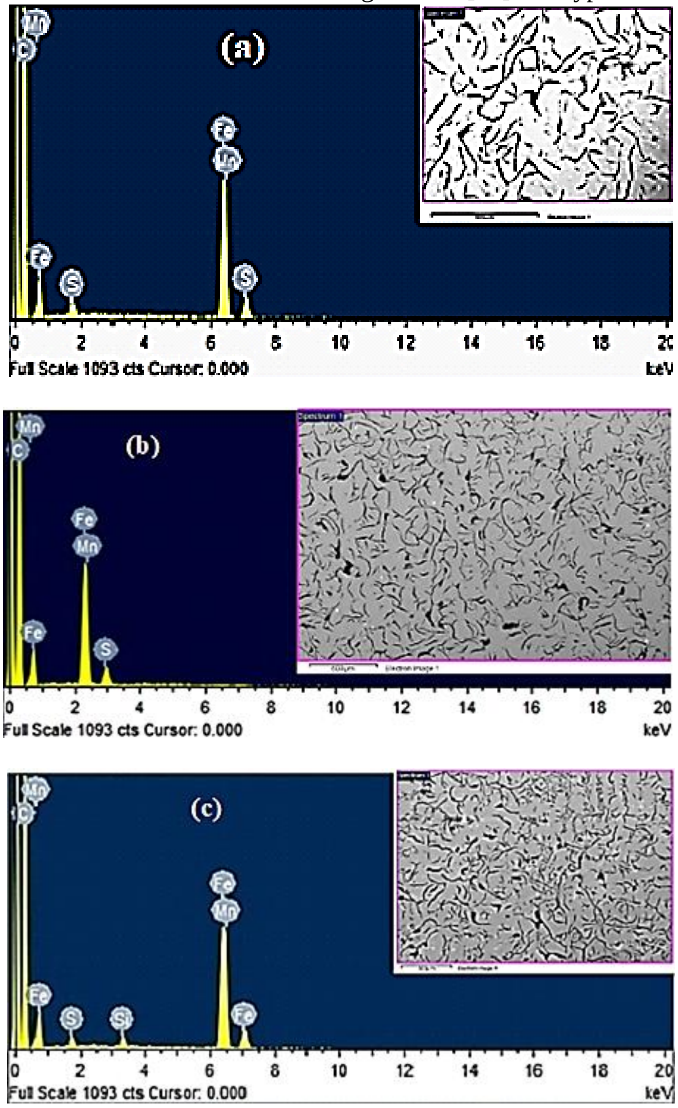

Fig. 3. EDS of Graphite - Ferrite microstructure of grey Iron as-cast in (a) 100% Silica mould (b) 100% Fe-Cr Slag mould and (c) 60% Fe-Cr Slag + 40% Silica Mould.

graphite morphology displayed is assumed to be as a result of significant changes in the heat capacities of the two moulding material existing together [6]. All EDS resultsfrom the as-cast samples are similar showing that there was no external contamination from the surrounding or the moulding materials, because the elemental composition remain the same for each as-cast product.

TABLE 1

ELEMENTAL COMPOSITION OF COMMERCIAL GREY CAST IRON BS1452 GRADE 250

Element	C	Si	S	P	Mn	Fe
%	3.2	2.1	0.1	0.6	0.7	BAL

C. Flake Graphite average size measurements

ImageJ software was used to evaluate thegraphite dimensions as simulated by the inbuilt features of this imaging editing software. The graphite flakes are found to be discrete flakes with different shapes and sizes in each as-castsamples. The standard deviation values of the graphite flakes size, length and intergranular spacing were determined from the micrographs of the scanning electron microscope. The schematic diagram for grain size measurementis as illustrated in figure 4(a-c) for each of the mould making material namely Silica, Fe-Cr Slag and mixed moulds respectively[20]. The detailed results ofthe graphite flake size measured for each as-castare as follows:

[A] Total area of graphite estimated in μm^3 are: 276.44 in 100% Silica mould; 8.65 in 100% Fe-Cr Slag and 11.56 in 60% Fe-Cr+40% Sand Mixture.

[B] String length of Graphite expressed in µm are: 63.12 in 100% Sand; 26.18 in 100% Fe-Cr Slag and38.62 in 60% Fe-Cr+40% Sand Mixture.

[C] Measured width of Graphite expressed in µm are: 13.34 in 100% Sand; 6.25 in 100% Fe-Cr Slag and 9.78 in 60% Fe-Cr+40% Sand Mixture.

[D] Particles of Graphite expressed in $/mm^2$ are: 95 in 100% Sand; 350 in 100% Fe-Cr Slag and 120 in 60% Fe-Cr+40% Sand Mixture.

The Silica mould samples shows the type B graphite flakes which has an average size of 63.12 µm, the Fe-Cr slag mould sample shows type A flakes which have an average graphite size of 26.18 µm. Lastly the mixed mould material sample exhibitedgraphite flake showing a mixture of type A and type B graphite flakes with an average size of 38.62 µm.

D. Mechanical properties evaluation

Fig. 5 (a-c) shows the toughness measured for each of the mould material used. It was found to be in the range of 72-74 HRC, 84-89 HRC and 74-78 HRC for Silica, Fe-Cr lag and the mixed mould respectively. This clearly shows improved hardness in Fe-Cr slag mould cast samplebetter than that found inSilica or Mixed mould material samples. The compressive and tensile behaviourof the samples are shown in Fig. 6 (a) and (b) respectively. The rate of deformation for the entire materials under examination is directly proportional to the load requirement. However, Slag mould cast shows higher strength values in compression, tensile and impact tests than that of the other two moulds. Interestingly appreciable deformation was noticed in the slag mould cast.Hence, the size of graphite flake definitely has an impact on the strength of the materials. The Slag mould castshows Type A graphite flakes which were fine and uniformly distributed in the iron matrix; in case of sand mould castings large size graphite flakes of type B were observed; and the mixed mould these flakes were observed to be combination of type A and type B. Therefore, the existence of smooth and uniformly distributed type Agraphite flakes enhanced the strength and ductility of slag mould cast products.

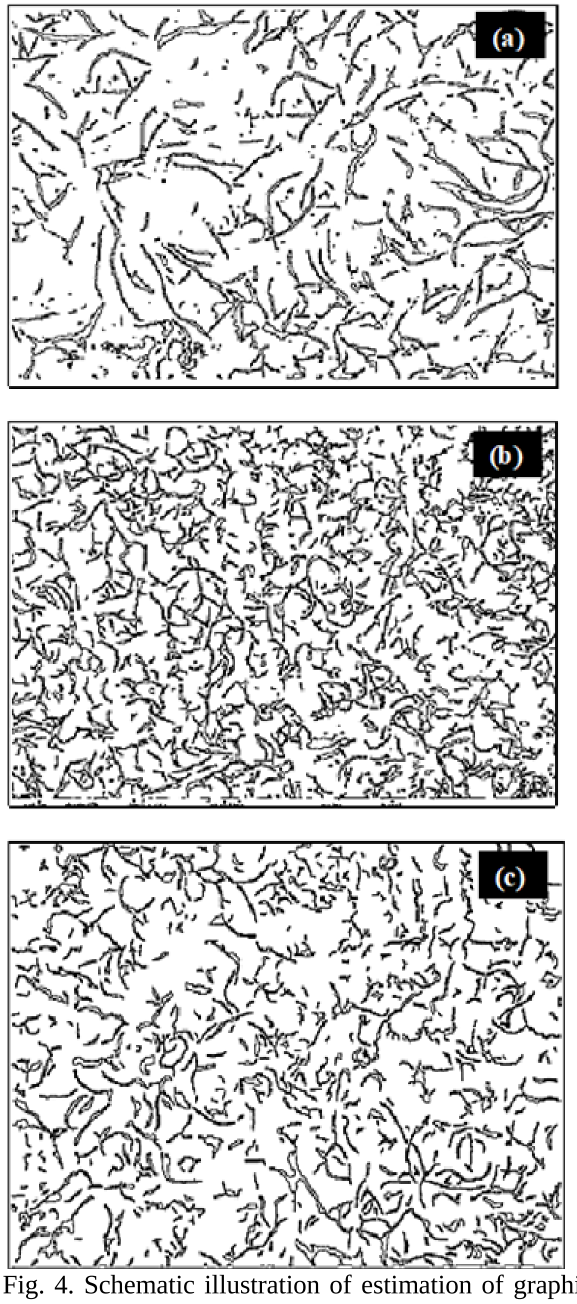

Fig. 4. Schematic illustration of estimation of graphite size using ImageJ software analysis in the as-cast samples of the 3 different mould materials. All the microstructure are graphite – ferrite (a) 100% Silica Sand (b) 100% Fe-Cr Slag and (c) combination of 60% Fe-Cr slag and 40% Silica sand.

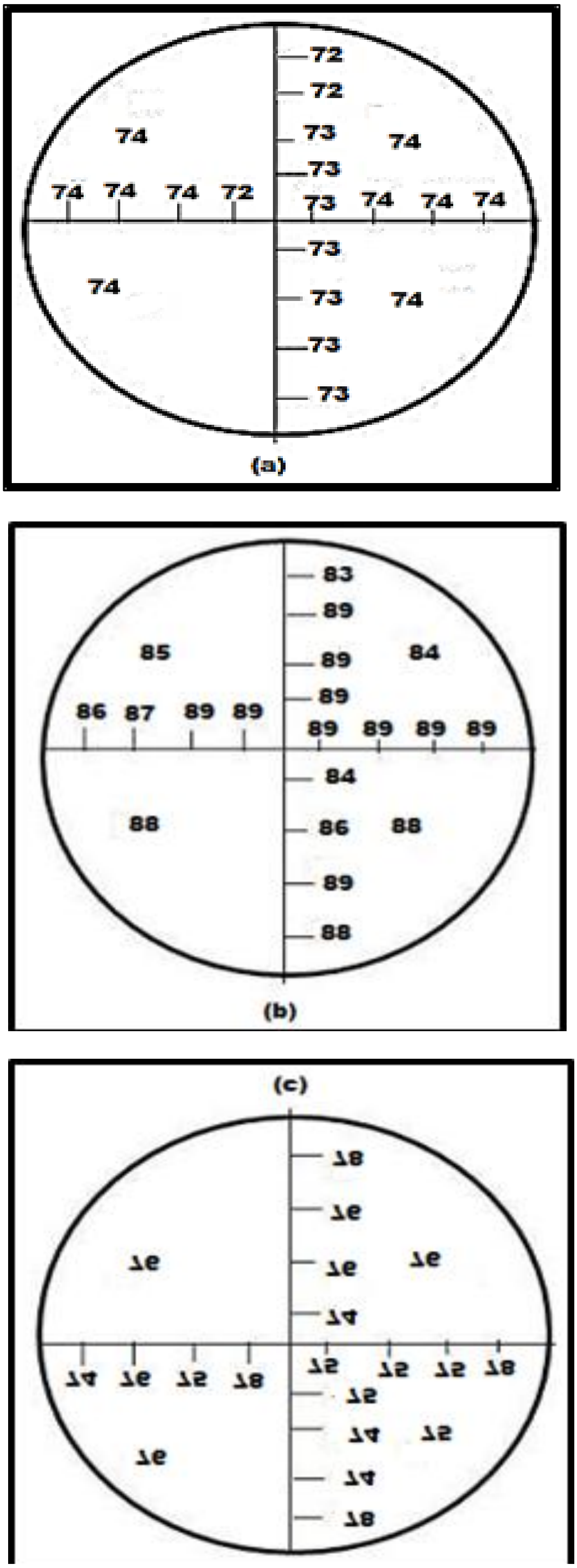

Fig. 5. Estimated Toughness (HRC) value range of the 3 sample moulds from Graphite - Ferrite microstructure of the grey iron samples in (a) 100% Silica;(b) 100% Fe-Cr Slag and (c) combination of 60% Fe-Cr slag and 40% Silica to give shape to the materials when it hardensfinish, measureable in terms of strength, enhanced structure that can be made visible and mechanical properties.

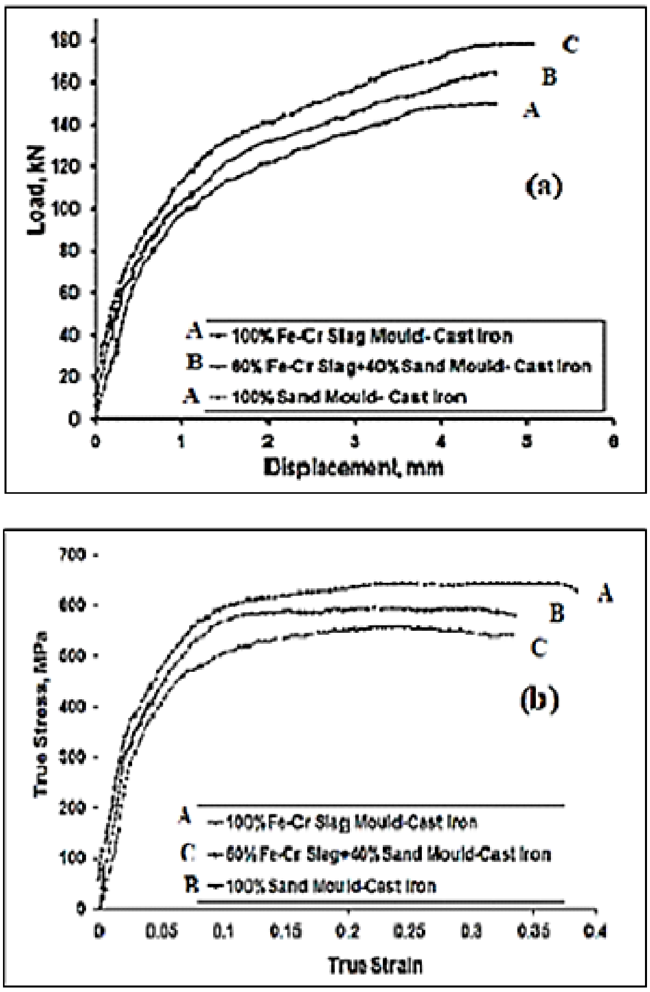

Fig. 6. Tensile characteristics of Graphite-Ferrite matrix microstructure of the grey cast iron castings made in Sand, Fe-Cr Slag and mixed moulds (height to width ratio equals unity): (a) Load-displacement curves (b) True stress – true strain curves

IV. CONCLUSIONS

For each as-cast sample microstructure of the same grey cast iron composition the only variable is the rate of cooling in the moulding material hence all the noticeable and estimated variables in morphology and mechanical properties estimated above are basically as a result of change in rate of the mould material heat dissipation which consequently affects the microstructure and fundamental mechanical properties of the as-cast samples as illustrated from this study. Casts were successfully performed under rapid heat transfer without noticing burning or fusing for each mould material used. Fe-Cr Slag mould cast yield uniform and smooth size of graphite in discrete flakes distribution as type-A in sand moulds and Type-B in iron matrix with both type been identified when is a mixed moulds. In addition rapid heat transfer of slag moulds should be subjected to the most favorable physical properties under the action toughness, compression and tensile to sand castings. Fascinatingly the ductility of graphitic microstructure cast iron casted in full Fe-Cr. Slag mould is far greater than the other moulds respectively. Better Impact toughness were noticed in slag mould castings compare to sand and mixed moulds. Furthermore, fractography analysis will be perform as future work in line with this research. In summary, Fe-Cr slag can be utilized in cast iron foundries as a substitute mould material for manufacturing castings with flat exterior

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REFERENCE

[1] Jones R.T, Economic and environmentally beneficial treatment of slags in DC arc furnaces. VII International Conference on Molten Slags, Fluxes and Salts, the South African Institute of Mining and Metallurgy, (2004).
[2] Narasimha Murthy I, Babu Rao J, Investigations on Physical and Chemical Properties of High Silica Sand, Fe-Cr Slag and Blast Furnace Slag for Foundry Applications, Procedia Environmental Sciences 35 (2016) 583 - 596.
[3] NiemelaPekka and MauriKauppi, Production,Characteristics and Use of Ferro Chromium Slags, Proceedings of Conference on Innovations in Ferro Alloy Industries- INFACON XI, New Delhi, India,(2007) 171-179.
[4] Diószegi A, Svensson I.L: On the Problems of Thermal Analysis of Solidification, Material Science and Engineering A, 413-414 (2005) 474 – 479.European committee for standardization- Brussels ENISO945-1:2008: E, Microstructure of Cast Iron Part-I; Graphite Classification by Visual analysis (ISO-945 1:2008).
[5] A. V Adedayo, Relationship between graphite flake sizes and the mechanical properties of grey iron, Int J.Materials Science and Applications .2 (2013) 94-98.
[6] ZeynepTaşliçukur, Gözde S. Altuğ, ŞeydaPolat, Ş. HakanAtapek, EnbiyaTüredi, Characterization of Microstructure and Fracture Behaviour of GG20 and GG25 cast iron materials used in valves, Metal 2012, 23 (2012) 1-6.
[7] Baker T.J, The fracture resistance of flake graphite cast iron, Int J. Materials in Engineering Applications.1 (1978) 13-18.
[8] Stefanescu D.M. et al: Cast Iron, ASM Handbook, Volume 15, ASM International, (1998) 168-176.
[9] Alex Muumbo, MitsuharuTakita and Hiroyuki Nomura, Processing of Semi-Solid Grey Cast Iron Using the Cooling Plate Technique, Materials Transactions, 44 (2003) 893- 900.
[10] Hideo Nakae, Effect of Graphite Morphology onTensileProperties of Flake Graphite Cast Iron, Material Transactions 42 (2001) 1428 – 1434.
[11] Nakae H, Influence of graphite morphology fractured surface in flake graphite cast iron measured by laserroughness meter, Int J. Japan Foundry EngineeringSociety 74 (2002) 644-649.
[12] Alex Muumbo, MitsuharuTakita and Hiroyuki NomuraYigit, Processing of Semi-Solid Gray Cast Iron Using the Cooling Plate Technique, MaterialsTransactions 44 (2003) 893 - 900.
[13] Bradley W. L, Srinivasan Malur, Fracture and fracture Toughness of cast irons, Int. Materials Reviews35(1990) 129-161.
[14] Adetunji O.R., Adegbola A.O., & Afolalu, S.A. (2015). Comparative Study of Case-Hardening and Water-Quenching of Mild Steel Rod on Its Mechanical Properties. International Journal of Advance Research, 3(6), 1-9.
[15] Dirisu, J.O., Asere, A.A., Oyekunle, J.A., Adewole, B.Z., Ajayi, O.O., Afolalu, S.A., Joseph, O.O., & Abioye, A.A. (2017). Comparison of the Elemental Structure and Emission Characteristics of Selected PVC and Non PVC Ceiling Materials Available in Nigerian Markets. International Journal of Applied Engineering Research. 12(23), 13755-13758.
[16] A. Abioye, O. P. Abioye, O. O. Ajayi, S. A. Afolalu, M. A. Fajobi and P. O. Atanda, Mechanical and Microstructural Characterization of Ductile Iron Produced from Fuel- Fired Rotary Furnace, International Journal of Mechanical Engineering and Technology 9(1), 2018. pp. 694–704
[17] Afolalu, S. A., Abioye, A. A., Dirisu, J. O., Okokpujie, I. P., Ajayi, O. O., & Adetunji, O. R. (2018, April). Investigation of wear land and rate of locally made HSS cutting tool. In AIP Conference Proceedings (Vol. 1957, No. 1, p. 050002). AIP Publishing.
[18] Afolalu, S. A., Abioye, O. P., Salawu, E. Y., Okokpujie, I. P., Abioye, A. A., Omotosho, O. A., & Ajayi, O. O. (2018, April). Impact of heat treatment on HSS cutting tool (ASTM A600) and its Behaviour during machining of mild steel (ASTM A36). In AIP ConferenceProceedings (Vol. 1957, No. 1, p. 050003). AIP Publishing.
[19] Afolalu, S. A., Okokpujie, I. P., Salawu, E. Y., Abioye, A. A., Abioye, O. P., & Ikumapayi, O. M. (2018, April). Study of the Performances of nano-case treatment cutting tools on carbon steel work material during turning operation. In AIP Conference Proceedings (Vol. 1957, No. 1, p. 050001). AIP Publishing.
[20] Udo, M. O., Esezobor, D. E., Apeh, F. I., & Afolalu, A. S. (2018). Factors Affecting Ballability of Mixture Iron Ore Concentrates and Iron Oxide Bearing Wastes in Metallurgical Processing. Journal of Ecological Engineering Vol, 19, 3.