

Effect of cooling rate on Microstructure - Properties Relationship of Grey Iron Cast in Sand and Metal Moulds

By

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Abstract

This study focuses on the effect cooling rate of different moulds on the microstructure (graphite flakes size, distribution) and mechanical properties of grey cast iron. Two common mould materials namely commercial silica sand and an industrial solid waste of Ferro chrome (Fe-Cr) slag were used. The moulds were produced using Sodium silicate-CO₂ process. Three kinds of moulds of Fe-Cr slag, silica sand and combination of these two were made. After ensuring optimum mould properties grey cast iron castings were performed on these moulds. The Cast iron was melted in and similar item of same geometry were cast successfully using these three different moulds. The results obtained reveal that Fe-Cr slag mould reveals faster cooling rates followed by mixed mould and finally sand mould. Faster heat transfer in slag moulds facilitated to obtain castings with fine microstructure, shorter and uniformly distributed graphite flakes. The microstructure result reveal ggraphite string lengths to be 26.18, 63.12 and 38.62 μm for castings made from the slag, silica sand and combination of these two moulding materials respectively. The effect of microstructure changes on the as-cast mechanical properties such as the hardness, tensile strength and creep properties were observed in each mould as-cast. Interestingly improved ductility and impact toughness has been observed in slag mould castings than either sand or mixed moulds. This improvement of ductility and impact toughness was observed to be 52% and 33% respectively. Fractography analysis of sand castings shows a rough and cleavage fracture surface due to the presence of large flaky structure of graphite in the iron matrix. Whereas in Fe-Cr slag mould castings which have a flake size of relatively smaller and uniformly distributed reveal largely mixed mode of fracture.

Keywords: Grey iron; Moulding sand; Fe-Cr Slag mould; SEM-EDS; Mechanical properties evaluation.

1.0 INTRODUCTION

Sand mould casting is the commonest process in foundry industry due its wide range of applications in making big castable sizes, its flexibility to produce any mould size, the ease of handling and its cost effectiveness. Currently, these benefits presented by sand castings have not been explored to their full potentials in many of the foundry units due to the depletion of high-grade natural silica sand. Therefore, the need to find suitable alternative material which will replace fully or partially the existing silica sand being used in high demand in various foundry shops. Meanwhile, attempts are now being made to using of industrial solid wastes like slags and fly ash to replace the green sand¹. However, very limited work has been reported

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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).

on re-use of various by-products or wastes generated in foundry industry. As a result of this, this study is to show case the usefulness of often wasted Ferro chrome (Fe-Cr) slag as moulding material in foundry shops. Fe-Cr slag has for long been classified as an 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% in by year 2025. However, it has been discovered that this slag has similar physical and chemical properties with silica sand and it readily available as industrial solid waste in large quantities². This paper is hereby giving a comparative effect of the rate of cooling of this moulding materials to that of green sand on the microstructure and mechanical properties of as-cast iron items. Finally, the study reveals the suitability of Fe-Cr slag as an alternative mould material in Grey Cast Iron foundries.

2.0 MATERIALS AND METHODS

Materials used in this study were highly refined silica sand and processed carbon Ferro Chrome (Fe-Cr) slag moulding material. Grey Cast Iron bar was sourced from commercial vendor. The moulds were prepared with optimum mould preparation specification with addition of sodium silicate along with CO₂ gassing to avoid porosity. Hence, for this study 3 different types of moulds were prepared; (1) with 100% Sand, (2) with 100% Fe-Cr slag and (3) with mixture of 60% Fe-Cr slag and 40% sand. Each of the mould was prepared individually. Thereafter, pieces of degreased grey cast iron were weighed and melted in a high temperature furnace at 1400 °C. Then the molten metal was poured into the prepared sand, slag and mixed mould cavities with a sufficient superheat and fluidity through sprue, runner and in-gates prepared in each mould of same geometry. Completely molten metal was poured in and made to fill each mould cavities. This was ensured with the aid of a riser fitted on each mould. Studies were performed to evaluate the mould heat transfer rates of Fe-Cr slag, sand, and mixture of these two moulds. The pouring time was kept constant since the mould dimensions were the same. The same was measured with solidification times by observing the mould temperature with a help of thermocouples placed at three different similar locations in each of the mould:- (1) near the runner, (2) on the riser and (3) mid-way of the mould cavity. The temperatures were taken and recorded simultaneously for each mould material. After cooling the as-cast from each mould were taken out from the mould boxes and subjected to microscopic and mechanical properties evaluations.

2.1 Metallographic Examination

Samples for metallographic observations were cut out and prepared by standard laboratory techniques. The microstructure and the elemental analysis of the as-cast obtained from sand, slag and mixed mould-materials were examined using Evo 60 Scanning Electron Microscope within built Energy Dispersive spectrum analysis. Nital (2% HNO₃) was used as etchant for the three specimens. Image J software was employed to determine the amount of graphite flakes present in each of the as-cast. Finally, average, and standard deviation values of this spacing were calculated from at least 90 measurements from SEM images.

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.

2.2 Mechanical Properties Evaluation

The as-cast products from sand, slag and mixed mould products were tested for mechanical properties such as:- hardness, tensile, compression and impact strengths were evaluated. The hardness values were taken using Rockwell hardness tester. Standard testing procedure was followed by applying the minor load of 10 kgf; and major load of 150 kgf with HRC scale. It was evaluated across the longitudinal and transverse directions of the samples; also measured at four different diagonals of the specimen and averaged. The tensile properties were evaluated as per ASTM E-8 standard. An average of three samples was tested from the each mould. The test was carried out at room temperature on computer-controlled servo hydraulic universal testing machine (Model: Fuel Instruments and Engineers (FIE-UTE100 with 1000 tons capacity) with a strain rate (0.5mm/min). On line load – elongation plots were obtained during the test. Compression tests were carried out on cylindrical specimens with aspect ratio H/D=1.0 (16 mm length and 16 mm diameter); the same were machined from the cylindrical finger castings of respective moulds. These cylindrical specimens were prepared using conventional machining operations of turning and facing. Standard samples were compressed by placing between the flat platens at a constant cross head speed of 0.5 mm/min using a computer controlled servo hydraulic 1000 Tons universal testing machine (model: FIE – UTE). Cold work dies made of steel was used as flat flattens. Notched bar impact tests were carried out as per ASTM-A370 standards. These tests were conducted using Charpy impact test machine (Model: R17 DT 63M4; Micro technology) with V-notched impact test standard dimensions of 10 × 10 × 55 mm. The test was repeated for three times for each casted sample. An average of three readings was considered to report the respective impact strength value.

3.0 RESULTS AND DISCUSSION

3.1. Cooling rate from each mould

The cooling rate of each mould was measured, recorded and plotted. The mould materials (sand, slag and mixed) heat transfer differs during solidification of the as-cast item. As explained earlier, this was done at three similar locations namely near the runner, riser, and midway on each of the mould. The obtained results was shown in figure 1(a-c). It clearly shows that the Fe-Cr slag mould shows more amount of mould temperature than either sand or the mixture of sand-slag moulds; this was true for all the locations under investigation. This more temperature in Fe-Cr slag mould provides a faster heat transfer rate than sand moulds. In general Fe-Cr slag particles have higher thermal conductivity than sand grains³; hence the moulds made with Fe-Cr slag particles exhibit more mould temperatures. Mould heat transfer rates during solidification plays a significant role in obtaining final microstructure and respective mechanical properties of the castings⁵

3 Niemela Pekka and Mauri Kauppi, 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.

5 Diószegi A, Svensson I.L: On the Problems of Thermal Analysis of Solidification, Material Science and Engineering A, 413-414 (2005) 474 – 479.

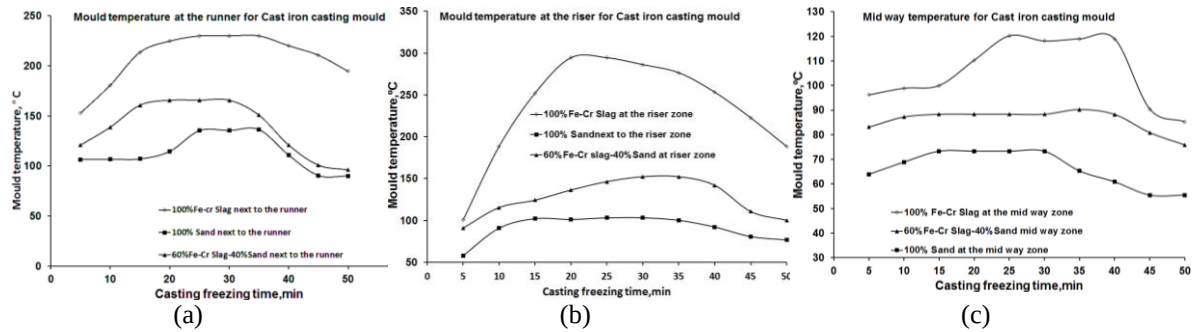


Figure 1: Variation in mould temperatures at various but similar locations during freezing of Grey Cast Iron castings for Sand, Fe-Cr slag and mixture of these two moulds materials: (a) near the Runner (b) near the Riser, and (c) Midway of the mould.

3.2 Microstructure evolution and evaluation

The microscopic analysis of the as-casted product in sand, Fe-Cr slag and mixture of sand and slag moulds are as shown in figure 2 (a-c) & 3 (a-c) respectively. The grey cast iron under consideration was a hypoeutectic alloy with a composition of 3.2% carbon, 2.1% silicon, 0.1% sulphur, 0.6% phosphorous, 0.7% manganese and balance iron. The graphite flake size, shape and type were examined as per the procedure described in EN ISO 945-1994 standards⁶. Grey cast iron casted in all the three moulds show uniform graphite flakes distribution in the iron matrix. However, sand mould cast product shows relatively sharp and long graphite flakes distribution in the matrix, figure 2(a). It might be due to the prevailing of low heat transfer rates in sand moulds which promotes a smaller number of nuclei presence with more grain growth; resulting a longer flake sizes in the iron matrix. According to the EN ISO 945-1994 standards these were categorized as type-B flakes. Whereas the cast products made from Fe-Cr slag moulds shows very fine and small size graphite flake with uniformly disturbed throughout the matrix, figure 2(b). The presence of this microstructure might be due to the existing of relatively faster cooling rates in slag moulds than sand. This type of flakes distribution termed as Type A graphite flakes and most desired morphology coupled with the best mechanical properties. Figure 2(c) shows the microstructure of grey cast iron casted in mixed mould of slag and sand; it consists the graphite flakes is in mixed with combination of fine and long flakes. The cooling rates of mixed moulds lie in between sand and slag moulds, hence the mixed graphite flakes appearing in these castings. This might be due to the significant changes in the heat storage capacity of the mould⁶. From ED's analysis it was clearly observed that no contamination from the ambience was entered into cast products during the casting.

⁶ European committee for standardization- Brussels ENISO945-1:2008: E, Microstructure of Cast Iron Part-I; Graphite classification by Visual analysis (ISO-945-1:2008), (2008).

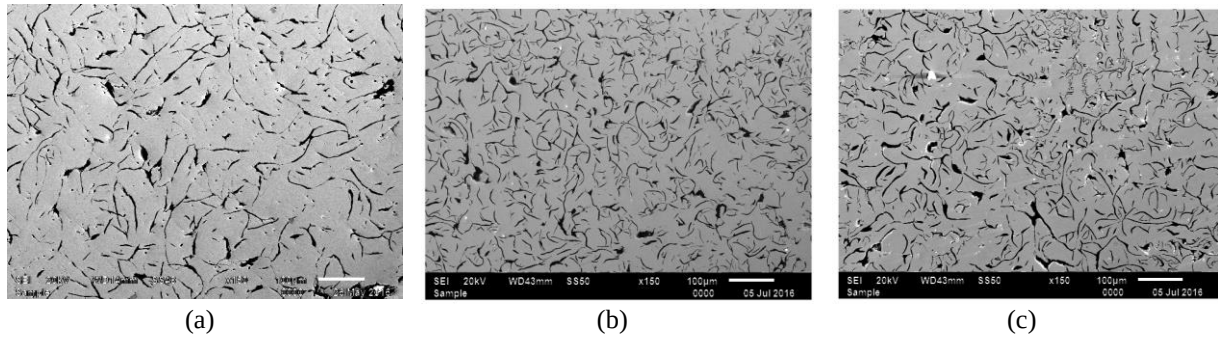


Figure 2: SEM-EDS of grey cast iron as-cast in (a) 100% Sand mould (b) 100% Fe-Cr Slag (c) 60% Fe-Cr Slag + 40% Sand Mould

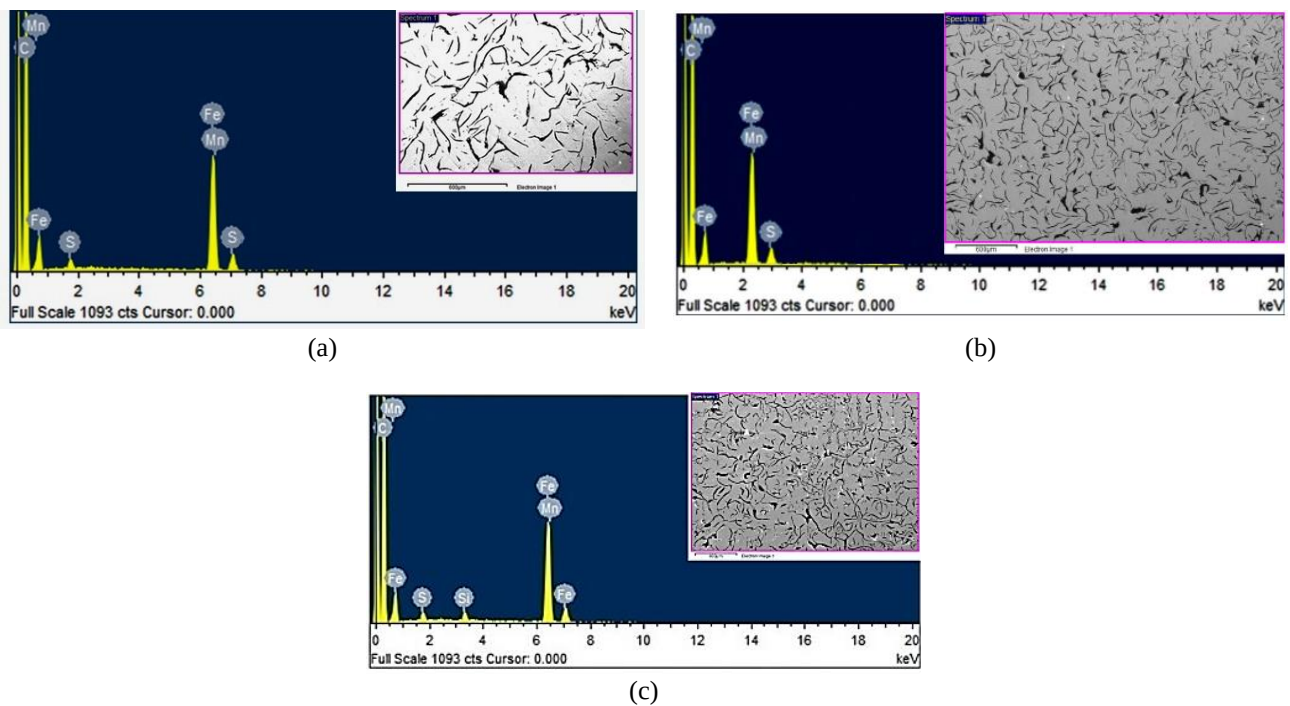


Figure 3: EDS of grey cast iron cast in (a) 100% Sand mould (b) 100% Fe-Cr Slag (c) 60% Fe-Cr Slag + 40% Sand Mould

3.3 Flake Graphite average size measurements

ImageJ software was used to estimate graphite flakes present in each as-cast⁷. The average flake size and standard deviation values of flakes spacing were calculated from respective SEM micrographs. The evaluation procedure was shown in Figure 4(a-c) for sand, slag and mixed moulds respectively. The detailed results on graphite flake size measurements of each castings were shown the Table 1. These results clearly show that sand mould exhibit type B

⁷ 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.

flakes with an average flake size of 63.12 μm ; for the same of Fe-Cr slag mould shows type A flakes with an average flake size of 26.18 μm . The mixed mould has been exhibits combination of type A and type B flakes with an average flake size of 38.62 μm .

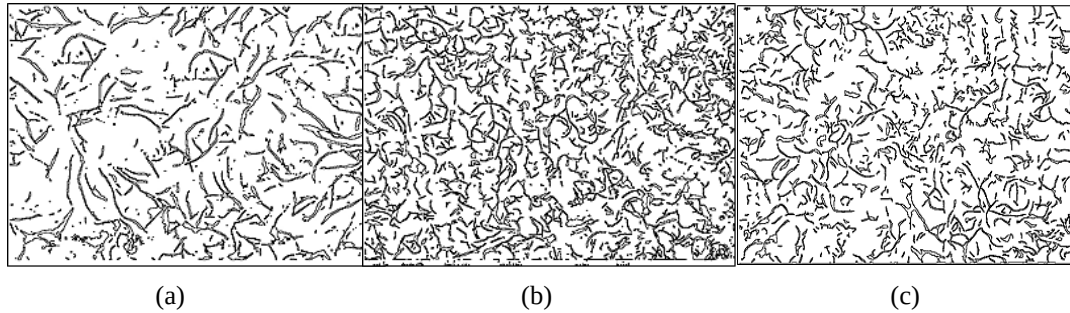


Figure 4: graphite size morphology profile of Grey cast iron casting samples using image analysis J software. (a) 100% Silica Sand (b) 100% Fe-Cr Slag and (c) Mixture of 60% Fe-Cr slag and 40% Silica sand.

Table 1: Measurement comparison of Silica Sand, 100% Fe-Cr Slag and the mixed mould

S.no	Graphite flakes measurements	Mould Materials		
		100% Sand	100% Fe-Cr Slag	60% Fe-Cr+40% Sand Mixture
1.	Graphite Area, μm^2	276.44	8.65	11.56
2.	Graphite String Length, μm	63.12	26.18	38.62
3.	Graphite Width, μm	13.34	6.25	9.78
4.	Graphite Particles, / mm^2	95	350	120

3.4 Mechanical properties evaluation

Figure 5 (a-c) shows the hardness profiles of grey cast iron castings made in sand, Fe-Cr slag, and mixture of slag – sand moulds respectively. It was found to be in the range of 72-74 HRC, 84-89 HRC and 74-78 HRC for sand, slag and mixed mould respectively. This clearly shows improved hardness in slag mould cast products than either sand or mixed moulds. Compression and tensile behaviour of the same was shown in figures 6 & 7 respectively; the summary of the obtained mechanical properties was shown in table 2. The load requirement increases with increase in deformation for all the materials under investigation. However, slag mould cast samples shows higher strength values in compression, tensile and impact tests than that of the other two moulds. Interestingly improved ductility was observed in slag mould castings; this increase was approximately 40% higher than that of the other two moulds. Graphite flake size has a significant effect on strength of the materials⁸. Slag moulds castings exhibited 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 moulds these flakes were observed to be combination of type A & type B. The enhancement of both strength and ductility of slag mould cast products might be

⁸ Zeynep Taşlıçukur, Gözde S. Altuğ, Şeyda Polat, Ş. Hakan Atapek, Enbiya Türedi, Characterization of Microstructure and Fracture behavior of GG20 and GG25 cast iron materials used in valves, Metal 2012, 23 (2012) 1-6.

due to the presence of fine and uniformly distributed type A graphite flakes.

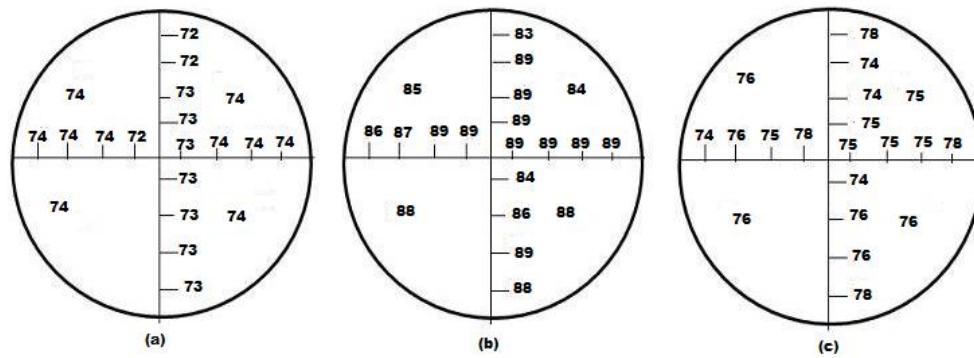


Figure 5: Hardness (HRC) profile of Grey cast iron castings along the cross section of the sample, cast in various moulds of: (a) 100% Silica Sand (b) 100% Fe-Cr Slag and (c) Mixture of 60% Fe-Cr slag and 40% Silica sand.

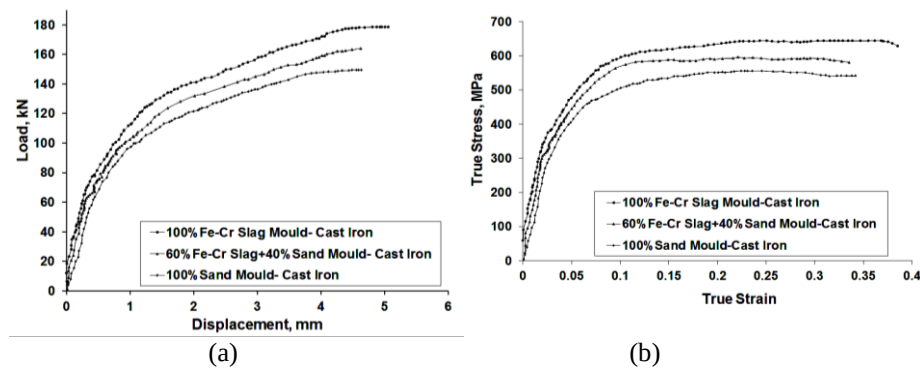


Figure 6: Compression behavior (with aspect ratio (H/D) =1.0) of Grey cast iron castings made in Sand, Fe-Cr Slag and mixed moulds: (a) Load-displacement curves (b) True stress – true strain curves

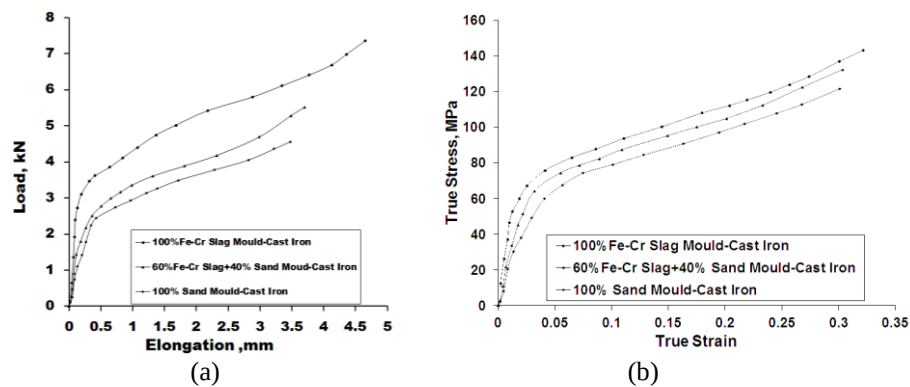


Figure 7: Tensile behavior of Grey cast iron castings made in Sand, Fe-Cr Slag and mixed moulds: (a) Load-elongation curves (b) True stress – true strain curves

Table 2: Mechanical properties of Grey cast iron made in sand, slag, and combination of these two moulds after compression, tensile and impact testing.

Material	Mould Material	Hardness	Tensile Properties				Compression Properties		Impact Strength (joules)
			Y.S (MPa)	UTS (MPa)	Break stress (MPa)	%Elongation	UTS (MPa)	Break stress (MPa)	
Gray Cast Iron	100% Sand	73 HRC	102	122	122	0.480	553	553	2.0
	100%Fe-Cr Slag	88 HRC	112	149	149	1.01	638	636	3.0
	60%Fe-Cr Slag + 40% Sand	76 HRC	105	133	133	0.89	592	591	2.4

3.5 Tensile and Impact Fracture studies

Figure 8 & 9 shows the SEM- EDS of tensile fracture surfaces of grey cast iron made in sand, Fe-Cr slag, and mixture of these two moulds respectively. These figures illustrate the effect of graphite flake size on decohesion with the matrix. The tensile fracture surface of the sand mould castings produce a rough fracture surface due to the presence of coarse /large flaky structure of graphite in the iron matrix, figure 8 (a); and the fracture surface shows a tendency to cleavage fracture^{9 – 13}. The matrix shows a tendency to cleave along pearlite-cementite interfaces within the eutectic matrix. This yields a much smoother fracture surface compared with samples made in slag and mixed moulds. Whereas for Fe-Cr slag mould castings produces a finer flake structure, and the flake size was relatively smaller and uniformly distributed throughout the matrix. Hence the fracture surface was largely mixed mode of fracture and it tends to follow along grain boundaries and exposing graphite flakes. Also it has been observed that due to the high content of graphite flakes they were occasionally pulled away from the iron matrix and leaving deep spherical cavities which was clearly visible in the SEM micrograph shown in figure 8 (b). Mixed mould castings yields a much smoother fracture surface compared with samples made in either slag or sand moulds, figure 8 (c). SEM-EDS of the impact fracture surfaces of all the three castings were shown in figures 10 & 11. Cleavage mode of fracture surface was observed in sand mould castings. This might be due to the weak bonding between graphite and matrix phase; also the presence of several micro voids surrounding the graphite. These voids induce a non-uniform distribution of stresses within the iron matrix. The graphite lamellas act as stress raisers producing self-micro cracking, or interfacial deboning at very low stress levels and leads to deformation in the matrix¹⁴. Whereas castings made from Fe-Cr slag moulds shows fine flake size structure; the fracture surface exhibits extensive local stretching with intermittent flat areas due to high content of graphite

⁹ Stefanescu D.M. et al: Cast Iron, ASM Handbook, Volume 15, ASM International, (1998) 168-176.

¹⁰ Alex Muumbo, Mitsuharu Takita and Hiroyuki Nomura, Processing of Semi-Solid Gray Cast Iron Using the Cooling Plate Technique, *Materials Transactions*, 44 (2003) 893- 900.

¹¹ Hideo Nakae, Effect of Graphite Morphology on Tensile Properties of Flake Graphite Cast Iron, *Material Transactions* 42 (2001) 1428 - 1434.

¹² Nakae H, Influence of graphite morphology fractured surface in flake graphite cast iron measured by laser roughness meter, *Int J. Japan Foundry Engineering Society* 74 (2002) 644-649.

¹³ Alex Muumbo, Mitsuharu Takita and Hiroyuki Nomura Yigit, Processing of Semi-Solid Gray Cast Iron Using the Cooling Plate Technique, *Materials Transactions* 44 (2003) 893 - 900.

¹⁴ Bradley W. L, Srinivasan Malur, Fracture and fracture toughness of cast irons, *Int. Materials Reviews* 35(1990) 129-161.

phase; which leads to a largely unidirectional brittle fracture mode was appeared in the matrix. In mixed mould castings the fracture behavior observed to be more or less similar to the slag mould castings with large graphite flake size structures.

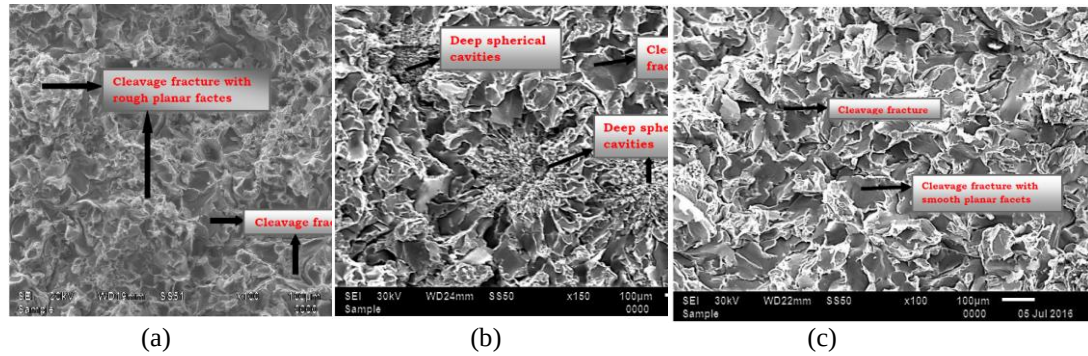


Figure 8: SEM micrographs for tensile fractured surfaces of Grey Cast Iron castings by various moulds: (a) 100% Sand (b) 100% Fe-Cr slag and (c) combinations of these two moulds.

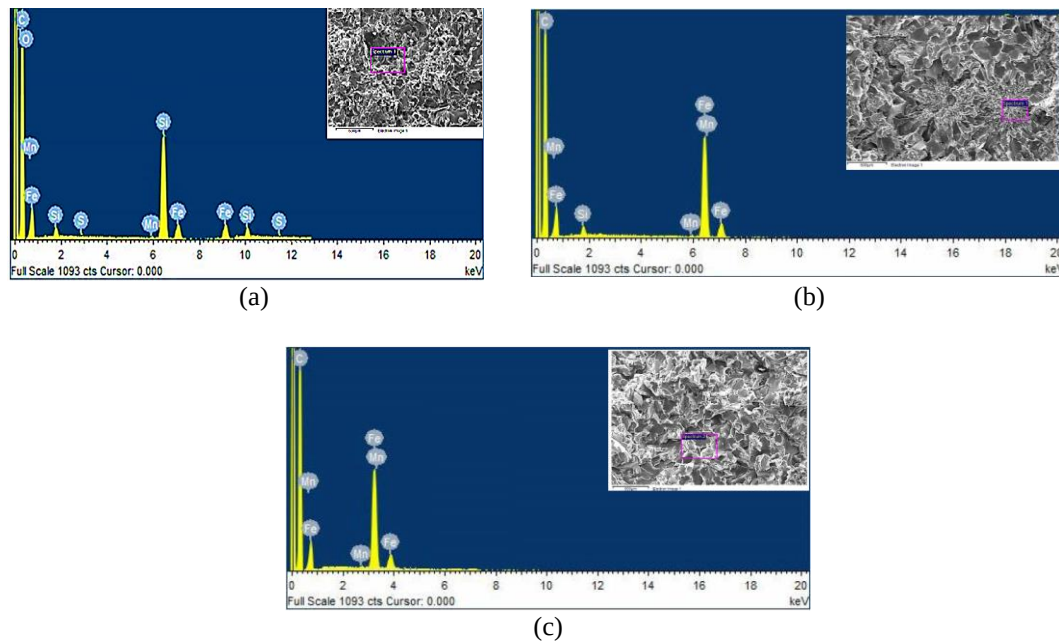


Figure 9: EDS of tensile fracture surfaces of Grey Cast Iron made by various moulds: (a) 100 % Sand (b) 100% Fe-Cr Slag (c) Mixture of Sand and Slag

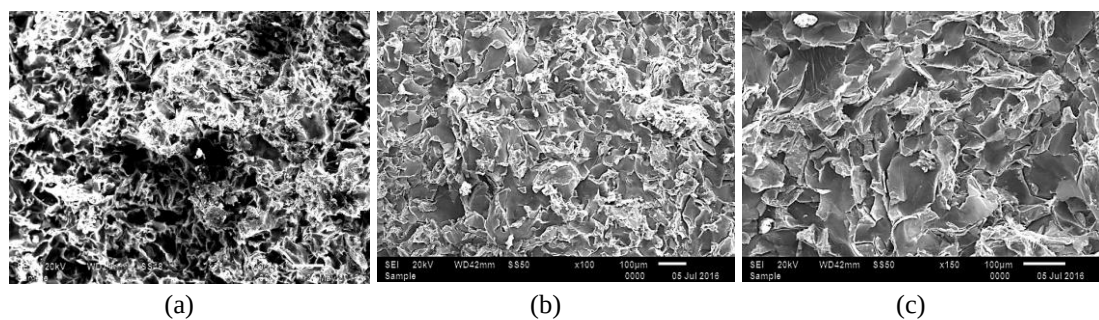


Figure 10: SEM micrographs for tensile fractured surfaces of Grey Cast Iron castings by various moulds: (a) 100% Sand (b) 100% Fe-Cr slag and (c) combinations of these two moulds

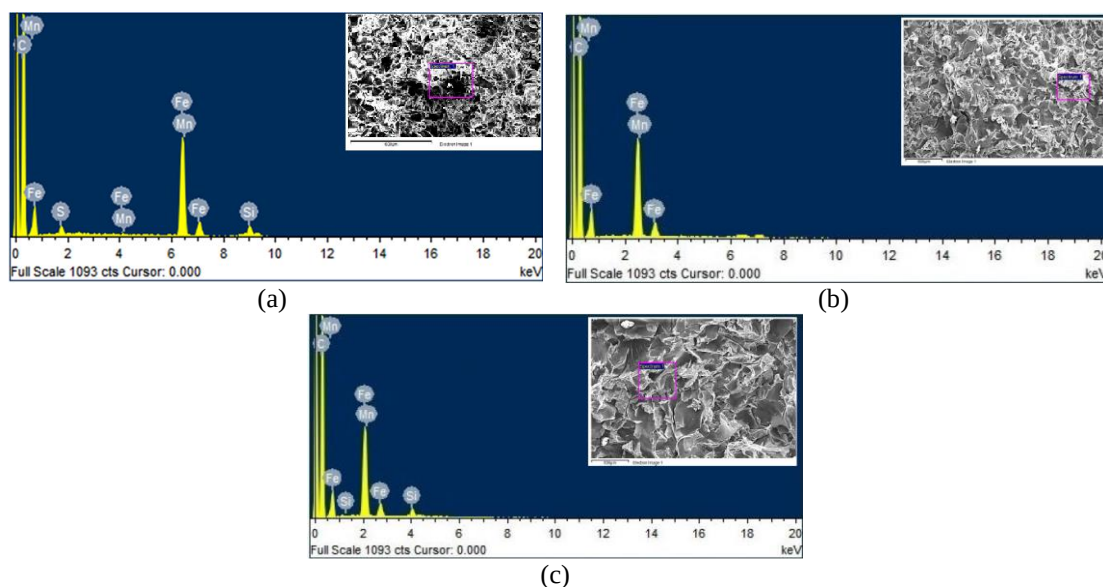


Figure 11: ED's analysis of Impact fractured specimen of Grey Cast Iron castings made by various moulds: (a) 100% Sand (b) 100% Fe-Cr slag and (c) combinations of these two moulds.

CONCLUSIONS

1. In all the three moulds grey cast iron castings (GCI) were performed successfully. Neither fusing nor burning was occurred in slag as well as sand moulds. Faster heat transfer rate was noticed in slag moulds.
2. Fe-Cr Slag mould cast products reveal uniform and fine size ($26.18\text{ }\mu\text{m}$) graphite flakes distribution in iron matrix. These flakes were categorized as type-A flakes; whereas in sand moulds long ($63.12\text{ }\mu\text{m}$) and non-uniform graphite flake distribution was noticed and categorized as type-B flakes. In case of mixed moulds both Type A and Type B flakes were noticed with an average flake size of $38.62\text{ }\mu\text{m}$.
3. Faster mould heat transfer of slag moulds enabled to have optimum mechanical properties like hardness, compression and tensile than sand castings. Interestingly the ductility of GCI casted in 100% Fe-Cr. Slag mould has significantly increased about 40% higher than the other two moulds.
4. Fractography analysis shows that cast iron castings made from slag and mixed mould exhibits similar fracture surfaces after tensile/ impact loading. Cleavage rupture is the dominant fracture type in sand mould castings; whereas castings made from slag and mixed moulds the fracture surface is largely in mixed mode of fracture.
5. Better Impact toughness were observed in slag mould castings than sand and mixed moulds.
6. In summary, Fe-Cr slag can be used in ferrous foundries in particular cast iron foundries as an alternative mould material to produce castings with smooth surface finish, dimensional stability with improved microstructure and mechanical properties.