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Microstructure, fluidity, and mechanical properties of semi-solid processed ductile iron

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Abstract This research is directed towards studying the effect of semi-solid processing (using cooling plate technique) on the microstructure, fluidity, and mechanical properties of ductile iron (DI). Sand mold castings with constant width of 25 mm and length of 150 mm with the thicknesses of 6, 12, 18, and 25 mm were used in this study. Microstructure, fluidity, and tensile strength properties were investigated as a function of fraction of solid. The results indicated that by increasing fraction of solid microstructure becomes finer and more globular. However, increasing primary fraction of solid increases the cementite content in the matrix. Above a certain fraction of solid ($f_s = 0.28$, $f_s = 0.1$, and $f_s = 0.05$ for 25, 18, and 12 mm wall thickness, respectively), the fluidity of semi-solid processed DI decreases steeply. For low fraction of solid ($f_s \leq 0.15$), increasing the fraction of solid results in an increment in the tensile strength, comparing with the ordinary DI due to the fine and globular structure formation. Any further increment of fraction of solid ($f_s > 0.15$) leads to the cementite increment and gas porosity formation, consequently the tensile strength decreased. The fraction of solid of DI and casting wall thickness should be considered in order to obtain the best combination of microstructure, fluidity, and mechanical properties of semi-solid processed DI.

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Introduction

The technological and economical potential of innovative materials and their processing are of increasing interest to technology oriented companies. The demands on cast parts for the automobile and aerospace industries, as well as in broad areas of the mechanical engineering sector are still rising. The demand for higher mechanical properties has to be combined with stringent economical and ecological aspects. These apparently inconsistent requirements have to be accomplished with the development of innovative manufacturing methods and material concepts [1].

As it has been long accepted that spherodization of graphite plays an important role in reforming the microstructure of cast iron leading to improvement of mechanical properties through minimization of interfacial cracking [2], researchers endeavored to improve the micro-structural characteristics of cast components by altering the shape of graphite and primary austenite from flaky and dendritic, respectively, to globular [3].

Although the superior processes such as thermo-mechanical processing, plastic deformation, and heat treatment have proved adaptable for a number of alloys, they are still to be considered as high cost and multi step processes to obtain fine and homogeneous structure. The ultimate goal of grain refinement is to obtain a fine grain, uniform, and equiaxed grain structure.

Semi-solid processing of ductile cast iron using cooling plate method has been reported in the literature [4] where, an improved structure of fine globular primary particles with a high degree of sphericity are obtained. However, the previous literature did not include any discussion on graphite, cementite, the matrix structure, and their effect on properties of ductile cast iron for wide range of primary fraction of solid. To know the relation among fraction of solid, castability, and cast properties obtained is very important in order to establish reasonable practical semi-solid process for ductile cast iron. In this study a combination between gravity casting and semi-solid processing using cooling plate was used. Although, cast iron produced by semi-solid processing [5–7] has defects due to fluidity (misrun and gases defects), it has a fine globular primary particles with a high degree of sphericity. The object of this research is to optimize the production of relatively high strength and homogenous structure ductile cast iron by semi-solid processing using direct pouring system with reasonable fraction of solid.

Experimental work

Melting and pouring samples

The iron alloy was melted in a 100 kg capacity medium frequency induction furnace with a silica lining and treated with Fe–Si–Mg alloy using a vortex method. Strips of the constant width 25 mm and the length 150 mm with the thicknesses of 6, 12, 18, and 25 mm, as shown in Fig. 1 were investigated in this study. In this work, side riser was designed by using modulus method and direct pouring from side riser [6, 8]. Pervious study [6] indicated that sound castings are obtained by pouring from side riser, especially, for low fraction of solid.

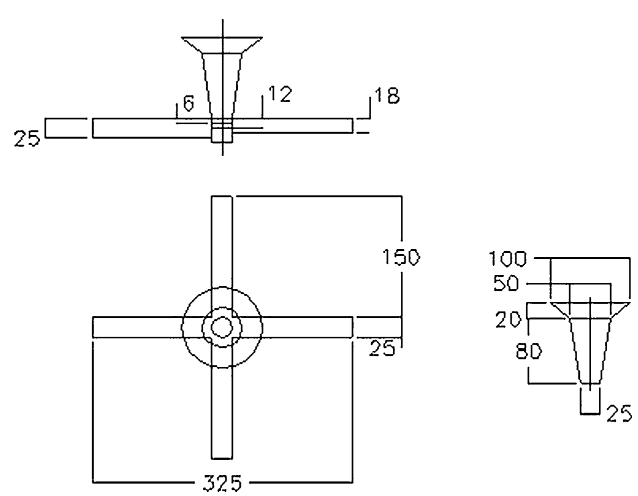

Fig. 1 Design used for casting specimens (unit in mm)

The chemical composition of iron samples is shown in Table 1. The melt charge of approximately 5 kg was removed from the furnace to the pouring system, at the desired temperature; the melt charge is poured over a cooling plate inclined at the known angle, Fig. 2, to the horizontal (10°) and to flow into the mold cavity. The temperature of liquid metal was measured by thermocouples inserted in the crucible and the mold.

Quenched cast iron samples just after inclined plate have been used in previous study [9] for verification of Scheil's equation to calculate the fractions of solid of cast iron processing in semi-solid state using cooling plate. This study shows a good agreement for fractions of solid measured by Scheil's equation and quenched cast iron samples, especially at low fraction of solid. For high fraction of solid the 5% deviation only was observed and was consider in this study. The primary fraction of solid corresponding to this temperature is calculated using Scheil's equation and the austenite distribution coefficient k has been determined by the model of Goettsch and Dantzig [10]. For controlling the fraction of solid many experiments are done and the temperature before and after the cooling plate are measured. It was noticed that the cooling plate for our pouring system decrease the slurry temperatures by nearly constant value 70 ± 3 °C. This constant value is considered and the controlling of fraction of solid is achieved by changing the poring temperature before cooling plate.

Table 1 Chemical analysis of cast iron samples and treatment alloys, wt%

	Ductile iron, DI, chemical composition	Treatment alloys for DI (Fe–Si–Mg)
C	3.11	–
Si	1.67	43–48
Mn	0.38	–
S	0.01	–
P	0.02	–
Ni	0.05	–
Cu	0.02	–
Co	0.02	–
Mg	0.06	8–10
Ca	–	1.5–2.8
Ce	–	0.51–1
Fe	Bal.	Bal.
CE%	3.67	
T_L	1226 °C	
T_S	1120 °C	

CE% is carbon equivalent = C% + [Si% + P%]/3

T_L, is liquidus temperature; T_S, is solidus temperature

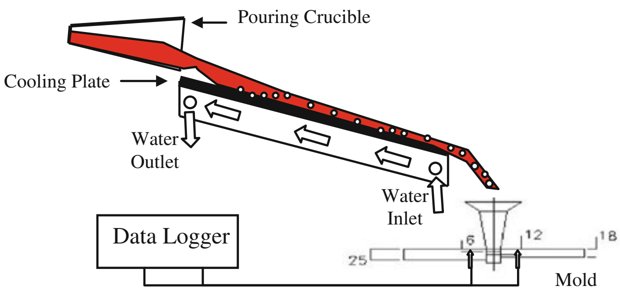

Fig. 2 Pouring system with cooling plate

Microstructure observation

Rectangular samples were cut from the strip casting. Microstructure and hardness measurement for cross-section surface at 20 mm distance from pouring base were studied. The microstructure was observed with optical microscope using ground and polished specimens. The primary austenite particles size, primary austenite particle sphericity, cementite, and graphite were measured and analyzed with image analysis software.

Fluidity test

The contours of the metal filling strips taken from the test castings were copied on paper by application of black dye [11], and accurately measured by scan gear toolbox and image analyzer. The area of each strip was obtained for sections of 6, 12, 18, and 25 mm. The percentage area thus obtained is considered to be measure of fluidity.

Mechanical test

Brinell hardness testes at 187.5 kg load were also performed. Specimens for tensile test were machined from 25 mm thickness strips. Tensile tests were carried out on round tension test specimens of diameter 6.5 mm and gauge length 25 mm. Tensile properties of the material were determined using ASTM E8.

Results

Microstructure

Solidification of ordinary hypoeutectic ductile iron begins with the precipitation of austenite dendrites from the melt as temperature falls under the liquidus. Figures 3 and 4 show the effect of fraction of solid on the structure of the semi-solid processed ductile cast iron with 25 and 6 mm wall thickness. It is clear that the ordinary ductile iron has a dendritic structure; on the other hand, the structure of

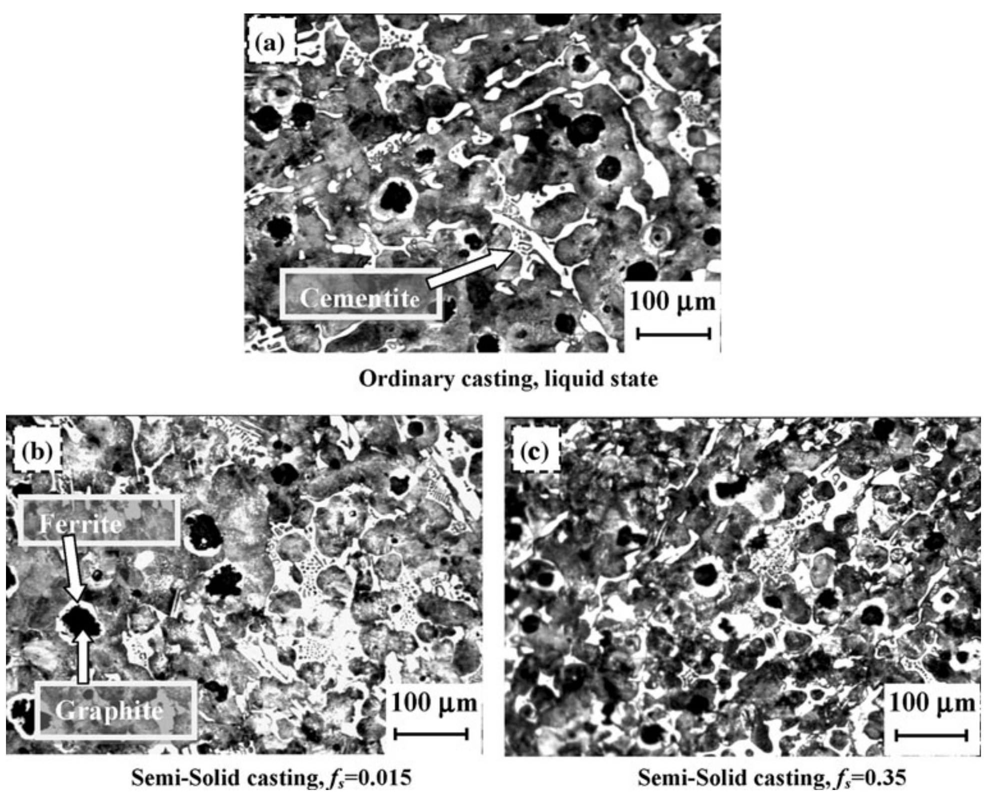

Fig. 3 Effect of fraction of solid on the structure of semi-solid processed ductile iron with 25 mm wall thickness. **a** Ordinary casting, liquid state. **b** Semi-solid casting, $f_s = 0.015$. **c** Semi-solid casting, $f_s = 0.35$

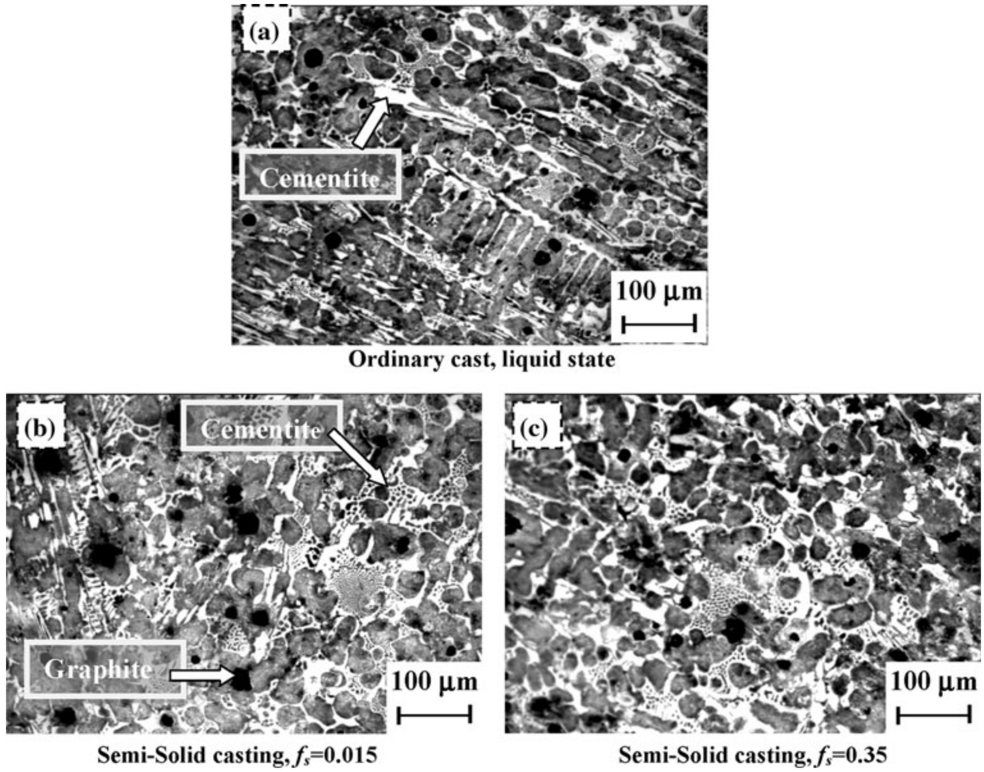

Fig. 4 Effect of fraction of solid on the structure of semi-solid processed ductile iron with 6 mm wall thickness. **a** Ordinary casting, liquid state. **b** Semi-solid casting, $f_s = 0.015$. **c** Semi-solid casting, $f_s = 0.35$

semi-solid processed ductile cast iron becomes finer and more globular by increasing fraction of solid.

As the metal cools down under the liquidus, austenite is precipitated and the liquid is progressively enriched in carbon until the eutectic composition (4.3%) is reached. Once this composition is attained, the remaining liquid transforms into two solids, graphite plus austenite in the case of the stable reaction. Once the eutectic solidification is completed, no liquid metal remains, and further reactions take place in the solid state [12].

The present and previous [9, 13] investigations are in good agreement in the point that shape and size of the primary austenite particles is highly affected with the use of cooling plate due to the resultant high cooling rate of the melt. High cooling rate of melt increases the number of the effective nuclei relative to the rate at which latent heat is dissipated. Moreover, mechanical fragmentations during the slurry flow over the surface of the cooling plate [4].

Figures 5 and 6 show that the fraction of solid has a considerable effect on the structure of produced ductile iron, where the increasing of fraction of solid increases the particle globularly and the amount of cementite as well as, decreases the primary particle grain size and graphite content.

Fluidity

Due to advanced solidification at the start of the pouring process, the liquid/slurry mixture flows with increased difficulty as the temperature decreases and the slurry approaches coherency. As shown in Fig. 7, there is perfect or near perfect filling of the cavity for 25 mm wall thickness up to 0.28 fraction of solid. As the wall thickness decreases and fraction of solid increases, the slurry flow resulted in incomplete filling of the mold cavity. Fluidity of the slurry is 100% over the range of fraction of solid from 0 to 0.28 for 25 mm wall thickness. It is clear that above a certain fractions of solid ($f_s = 0.28, f_s = 0.1$, and $f_s = 0.05$ for 25, 18, and 12 mm wall thickness, respectively), the fluidity of semi-solid processed DI decreases steeply. As a result, the fraction of solid at which the fluidly decreases steeply has been defined as a critical fraction of solid. The procedure used to measure the critical fraction of solid is made by construction a horizontal line at a value 5% below the maximum filling area level, intersecting the curves at different critical solid fraction values.

In a previous study [5] similar behavior has been found out for semi-solid casting of gray cast iron by measuring the filling area at various fractions of solid. By increasing the fraction of solid, the slurry viscosity increases rapidly

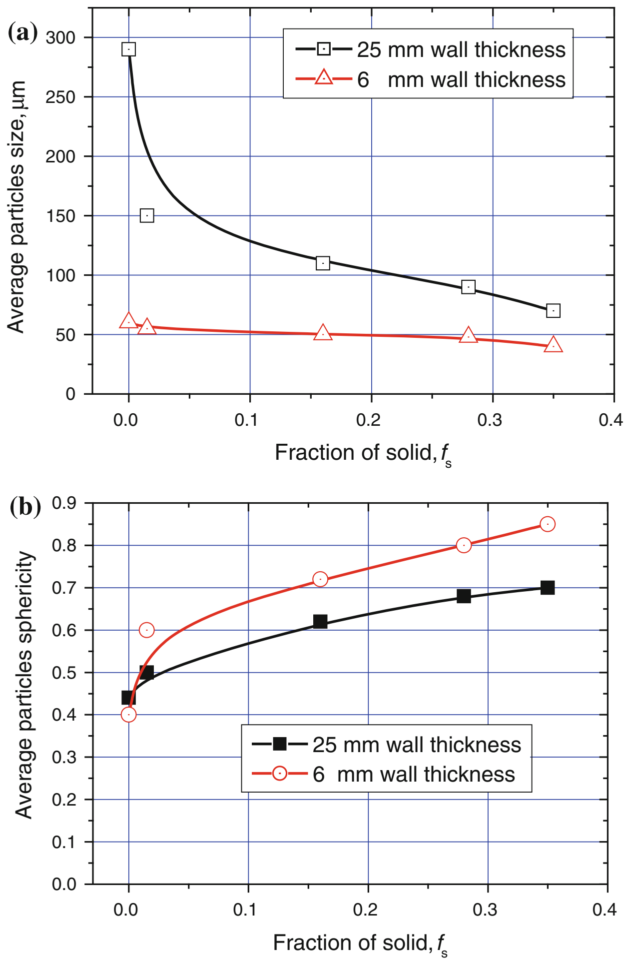

Fig. 5 Effect of fraction of solid on average particles size and particles sphericity of semi-solid processed ductile iron

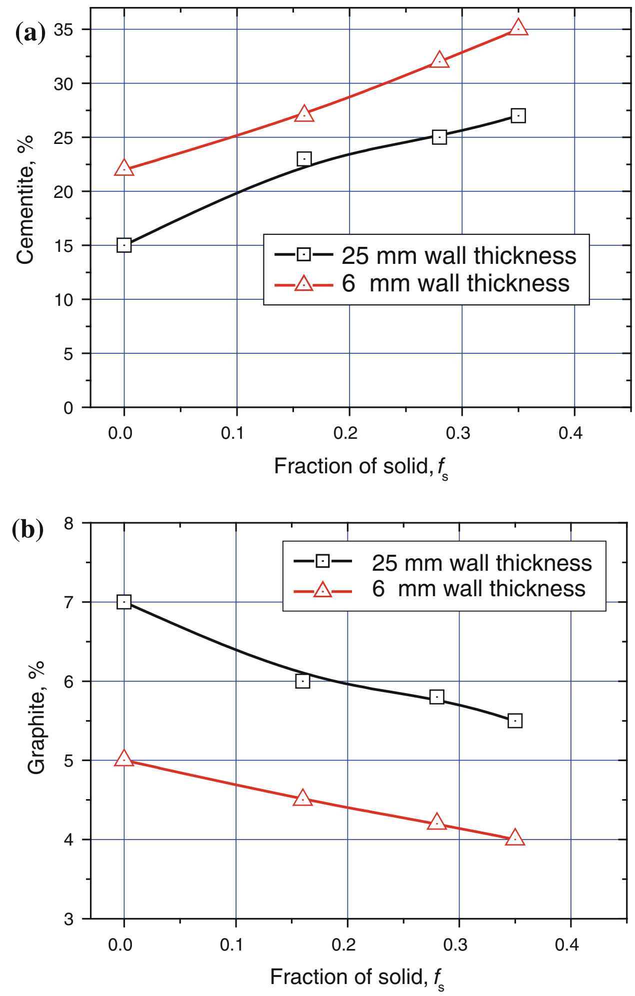

Fig. 6 Cementite and graphite as a function of fraction of solid of semi-solid processed ductile iron

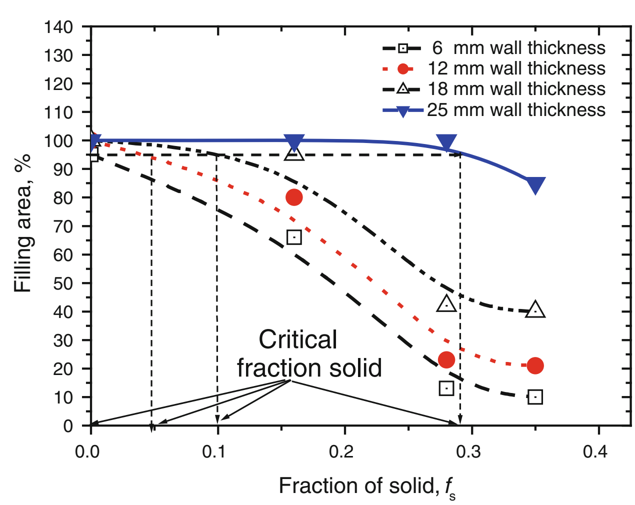

Fig. 7 Relation between primary fraction of solid and filling area %

accompanied by a decrease in its velocity and solidification throughout the cross-section near the tip [6, 14]. At this instant it will close the mold section and prevent the slurry from flowing further. Figure 8 shows the relation between critical fraction solid and casting wall thickness. Here, it is very important to carefully select the suitable fraction of solid for every casting wall thickness in order to obtain perfect filling of the mold cavity. The critical wall thickness is important for ensuring reasonable fluidity in semi-solid processed ductile iron casting design.

Mechanical properties

Hardness values are shown in Fig. 9 as a function of fraction of solid. Hardness generally increases by increasing fraction of solid. The present and previous [7, 15] investigations are in good agreement in the point that carbide formation are found in usual cast iron with a higher amount of undercooling. The undercooling may occur by the higher cooling rate due to the higher fraction of solid.

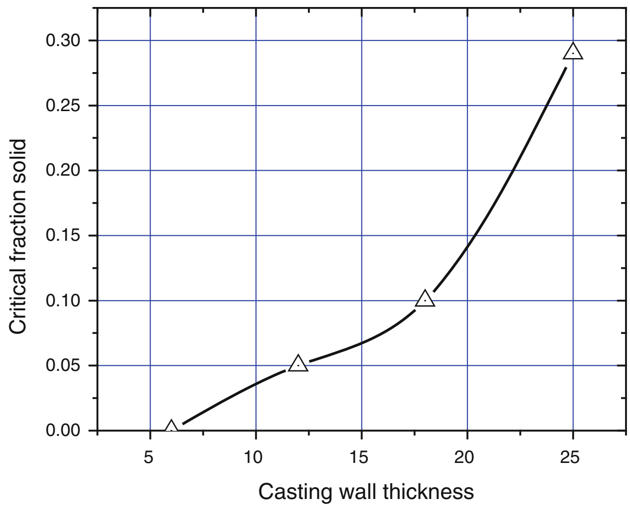

Fig. 8 Critical fraction solid as a function of casting wall thickness

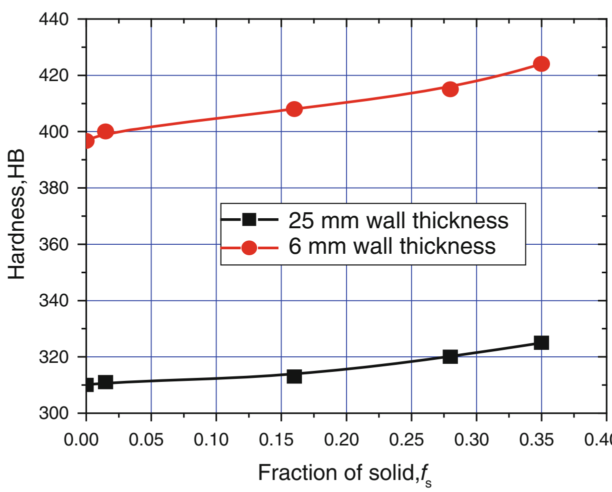

Fig. 9 Brinell hardness as a function of fraction of solid for 25 and 6 mm wall thicknesses

Finally, we can say that although the cooling plate has a refining effect on primary austenite, it causes an increasing in carbide amount in the microstructure. Figure 9 shows that the 6 mm wall thickness has a higher hardness than 25 mm wall thickness due to higher cooling rate for the remaining liquid in (liquid–solid) slurry inside the mold.

Figure 10 shows the effect of fraction of solid on both ultimate tensile strength and 0.2% offset yield strength for semi-solid processed DI. For low fraction of solid ($f_s \leq 0.15$), increasing fraction of solid results in an increment of the tensile strength, comparing with the ordinary DI due to the fine and globular structure formation (see Figs. 3b, 4b, 5). Further increase in fraction of solid ($f_s > 0.15$) leads to the cementite increment and gas porosity formation, consequently the tensile strength decreased. This study and the pervious one [6] are in a good agreement that increasing fraction of solid in slurry gives the chance of macro porosity formation, especially, for fraction of solid more than 0.2. The appearance of macro porosity in high fraction of solid seems to be principally caused by shorter time of solidification and it will not allow gases to escape from the cast and yields macro porosity in cast product. At higher fraction of solid ($f_s \geq 0.28$) gas porosity in all DI final samples was observed. DI is relatively high sensitive to the gas porosity formation resulting from high turbulence cooling plate pouring system.

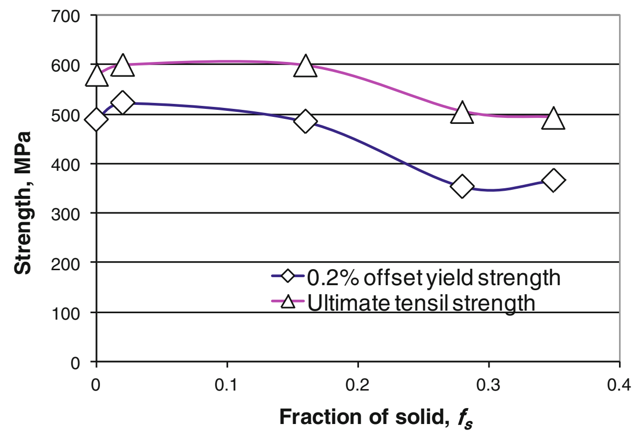

Fig. 10 Strength as a function of fraction of solid

Finally, it can be observed from the current result that a combination of microstructure, fluidity, and mechanical properties have to be considered in order to produce net shape high quality semi-solid processed ductile iron using cooling plate technique.

Conclusion

The effect of the semi-solid processing on the solidification microstructure and hardness of ductile iron was investigated. Increasing the fraction of solid leads to the following conclusions:

1. Microstructure refinement and formation of more globular structure.
2. Fluidity of semi-solid processed DI decreases steeply as the fraction of solid increases above certain critical value depending on casting wall thickness.
3. Increasing the fraction of solid increases the hardness values, this is explained by the cementite increment and the fine globular structure formation.
4. Tensile strength of the semi-solid processed DI is relatively high compared with ordinary one for low fraction of solid ($f_s \leq 0.16$). Further increase in fraction of solid ($f_s > 0.16$) leads the cementite

increment and gas porosity formation, consequently the tensile strength decreases.

5. The fraction of solid and the wall thickness should be considered in order to obtain the best combination of microstructure, fluidity, and mechanical properties of semi-solid processed DI castings.

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