Fabrication of Ductile Iron with High Manganese

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Abstract: This study investigates the production of ductile iron with increased manganese content up to 0.56 wt.% to optimize mechanical properties and reduce material costs. Typically, manganese content is restricted below 0.35 wt.% to preserve elongation, thus raising production expenses due to reliance on low-manganese scrap. By employing controlled inoculation (0.4 wt.%) and nodularization (1.2 wt.%), ductile iron containing higher manganese was successfully cast without significantly compromising nodularity or ductility. Microstructural analysis revealed that manganese promoted pearlite formation, reducing ferrite content yet maintaining nodularity above 90%. The resulting ductile iron exhibited increased tensile strength due to refined pearlitic structures, though elongation slightly decreased. Additionally, casting simulations optimized mold design and process parameters, ensuring defect free, consistent quality. These findings demonstrate the feasibility of utilizing higher manganese contents, enhancing flexibility in raw material selection and reducing manufacturing costs while satisfying critical mechanical performance requirements.

Keywords: Ductile iron, ferrite, pearlite, high maganese

1 Introduction

Ductile iron, also known as spheroidal graphite iron, has been extensively studied and developed over the past six decades, becoming a critical engineering material due to its advantageous combination of mechanical properties. These properties effectively merge the hardness and castability typical of gray cast iron with the superior ductility and toughness characteristic of steel, making it widely employed in the manufacturing industry for various demanding applications. The mechanical properties of ductile iron are predominantly influenced by its microstructure, which, in the as-cast state, generally comprises graphite nodules dispersed within a ferritic, pearlitic, or ferritic-pearlitic matrix.

The specific properties of ductile iron are dictated by the relative proportions of ferrite and pearlite in the matrix. Ductile iron with a predominantly ferritic matrix exhibits enhanced ductility, elongation, and toughness, but reduced yield strength, tensile strength, and hardness. Conversely, ductile iron with a pearlitic matrix displays increased strength and hardness but reduced elongation and ductility. The microstructure and mechanical properties are thus highly sensitive to chemical composition, processing parameters, and cooling conditions.

Significant research efforts have focused on understanding the influence of various alloying elements on the graphite morphology and matrix structure of ductile iron. Among these, silicon, manganese, copper, nickel, molybdenum, and niobium have received considerable attention due to their pronounced effects. For instance, silicon is known as a ferrite stabilizer and strongly promotes graphitization. Glavas et al. [1] investigated the effects of varying silicon contents (3.11-5.42wt.%), confirming that increased silicon concentrations enhance ferritic matrix formation and subsequently improve tensile and yield strength as well as elongation.

On the other hand, Sertucha's analysis [2] of 68 as cast ferritic nodular iron samples showed that increasing silicon content boosts tensile strength, yield strength, and hardness but reduces elongation and impact energy at room temperature, 220 °C, and 240 ° C. In contrast, nickel only affects room temperature tensile properties, and at 0.27 wt% has no measurable impact on impact energy. The study by Moritz Riebisch et al. [3] demonstrated that Manganese and niobium mildly promote pearlite formation and enhance tensile strength of high silicon SSDI without appreciable loss of ductility, whereas molybdenum keeps pearlite below 5% only at short solidification times but reduces elongation when solidification is prolonged.

In response to ongoing demands for high performance yet cost effective materials, recent attention has shifted towards exploring ductile iron compositions with increased manganese content[4]. Manganese, introduced into the iron melt as an alloying element, dissolves into the iron matrix and significantly promotes pearlite formation. It has been observed that manganese content within the range of 0.4 - 0.6 wt.% or higher can induce a shift from a ferritic to a pearlitic matrix. Furthermore, manganese interacts with sulfur, forming manganese sulfide (MnS), which acts as heterogeneous nucleation sites. While manganese additions improve tensile strength and hardness, they simultaneously reduce ductility and elongation. Excessive manganese concentrations, however, can result in segregation at intercellular regions, adversely affecting the mechanical integrity of the final product [5].

To optimize casting quality and process efficiency, computational simulation has become an indispensable tool. Metal casting simulation software can accurately model the entire casting process, from metal pouring through solidification, enabling the prediction and prevention of potential casting defects. Consequently, simulation technologies facilitate optimized mold designs, reduced material waste, and enhanced product quality by preemptively addressing manufacturing issues prior to actual production.

The primary objective of this study is to comprehensively evaluate the effects of high manganese content on the microstructure and mechanical properties of ductile iron. Additionally, the research aims to optimize casting processes and ensure consistent product quality through the application of advanced simulation techniques. Conventionally, manganese levels have been strictly controlled below 0.35 wt.% to maintain required elongation levels. Achieving such manganese control necessitates using high quality steel scrap with low manganese content, significantly raising production costs. This research successfully demonstrates the feasibility of producing ductile iron with manganese content as high as 0.55 wt.% without compromising mechanical performance, thus enabling the utilization of more diverse and cost effective raw material sources.

2 Experimental procedure

After calculation with right ratio, raw materials (Table 1.) was melted in medium frequency induction furnace (1000kg in capacity). After melting, the contents in carbon, silicon and other selected alloying elements were checked and adjusted to the specified values (%C= 3,7 ÷ 3,9; %Si= 1,5 ÷ 1,7; %Mn = 0.3÷0.6). When temperature increased to 1530-1540 0C, poured to reactor for treatment with nodulariser (about 0.2wt.% of liquid metal). After completion of the reaction, the treated batches were transferred to the pouring ladle (with nodulariser of about 0.2wt.% of liquid metal), where the alloys were cast in green sand moulds.

The tensile test pieces of 14 mm in diameter were machined from Y-blocks. The dimensions and the shape of the test pieces are in accord- ance with EN 1563:2012. The tensile test was carried out in accordance with EN ISO 6892-1:2009. After tensile test, fracture surfaces of test pieces were observed under scanning electron microscope (SEM). Test pieces for the metallographic examinations were taken from the tensile test pieces after the tensile test. Microstructure features (nodularity, nodule count (expressed as number of graphite nodules/mm^2), ferrite content and pearlite content were determined using a light metallographic microscope with a digital camera and the image analysis system. Determination of nodularity and nodule count was carried out in accordance with ASTM E2567-14. Graphite particle was considered as a nodule if the value of its roundness shape factor exceeds 0,9.

Table 1. Raw materials.

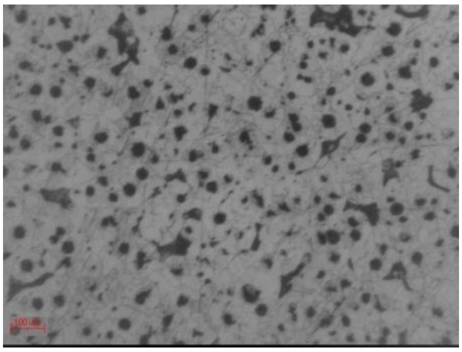
Type/Name	C	Si	Mn	Cr	Cu	P	S	Fe
Steel chunk	0.5	0.22	0.65	0.12	0.13	≤0.02	≤0.02	Balance
Steel S48C	0.5	0.21	0.64	0.14	0.12	≤0.02	≤0.02	Balance
Cast iron (Ingot)	4.2	0.2	0.05	-	-	≤0.04	≤0.015	Balance
Ductile iron	3.7	2.4	0.45	-	-	≤0.06	≤0.02	Balance

3 Results and Discussion

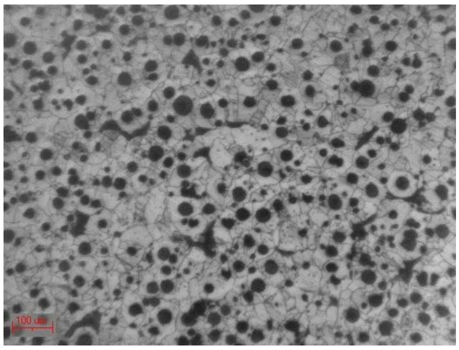
3.1 Microstructure

The microstructural characteristics of ductile iron with varying manganese content were analyzed systematically. Figure 1 illustrates typical microstructures observed at manganese contents below 0.4%, characterized by high nodularity approximately 95% and predominantly ferritic matrix structures around 70% ferrite. Such microstructural configurations are favorable for achieving optimal ductility and toughness.

Table 2 provides detailed chemical composition data for the cast samples, offering further insights into the correlation between manganese content, carbon equivalent (CE), and magnesium residuals. Samples with lower manganese (0.32% - 0.40%) showed stable nodularity (above 94%) and maintained consistent carbon equivalent values around 4.45, indicating minimal impact on carbon saturation and solidification characteristics. With manganese increasing to 0.53% and 0.56%, the CE remained within the acceptable range (4.46 - 4.49), yet the magnesium residual values exhibited a slight decrease from around 0.04% to approximately 0.03%. This reduction in magnesium residuals at higher manganese contents could be indicative of manganese interacting with residual sulfur, slightly decreasing the effectiveness of magnesium in nodularizing the graphite. Consequently, precise control of manganese and magnesium is essential to maintain optimal nodularity and overall microstructural quality.



a) Sample 2 with 0.36% Mn



b) Sample 3 with 0.4 % Mn

Figure 1. Microstructure of ferritic ductile iron

Table 2. Chemical composition of casting samples

No.	Composition (%)						
	C	Si	Mn	P	S	CE	Mg residual
Standard	**3.5-4.5**	**2-2.7**	**0.3max**	**0.06max**	**0.03max**	**4.45**	**0.04**
01	3,65	2,64	0,32	-	-	4,44	0,04
	3,66	2,65	0,32	-	-	4,45	0,04
	3,64	2,64	0,32	-	-	4,43	0,04
02	3,71	2,63	0,36	-	-	4,50	0,035
	3,7	2,61	0,36	-	-	4,48	0,034
	3,73	2,59	0,36	-	-	4,51	0,036
03	3,7	2,62	0,4	-	-	4,49	0,033
	3,73	2,59	0,4	-	-	4,51	0,029
	3,71	2,65	0,4	-	-	4,50	0,031
04	3,7	2,55	0,53	-	-	4,46	0,027
	3,72	2,58	0,53	-	-	4,49	0,034
	3,68	2,62	0,53	-	-	4,47	0,028
05	3,73	2,53	0,56	-	-	4,49	0,033
	3,67	2,65	0,56	-	-	4,46	0,04
	3,69	2,57	0,56	-	-	4,46	0,037

Increasing the manganese content to 0.53 % and 0.56 % led to a reduction in ferritic content to approximately 65 % and 56 %, respectively, and a slight decrease in nodularity to 94 % and 91%. This phenomenon occurs as manganese, a known pearlite-stabilizing element, promotes pearlite formation by dissolving into the ferrite matrix and accumulating at eutectic grain boundaries, thus reducing ferrite content.

Further examination indicated a critical threshold at 0.56% manganese content. Exceeding this level leads to nodularity dropping below 90%, severely compromising mechanical properties. Thus, the research delineates an optimal manganese content up to 0.56%, allowing broader flexibility in raw material selection without compromising microstructural integrity.

Figure 2 provides additional visual confirmation of these microstructural changes at higher manganese levels. Micrographs clearly demonstrate the reduction in ferrite content and a corresponding increase in pearlite formation. At 0.53% manganese, pearlite is noticeably increased, and nodularity remains relatively high, reflecting minor deterioration. However, at 0.56% manganese, a significant reduction in ferritic content is visually evident, along with increased pearlite formation, resulting in decreased nodularity. These observations longation [5].

The enhanced tensile strength can be attributed to manganese's ability to refine pearlite grains and induce lattice distortions, which subsequently reduce the distance between ferrite grains. Additionally, manganese's interaction with residual sulfur forms manganese sulfide, serving as heterogeneous nucleation sites, thus positively affecting nodularity. However, excessive manganese content led to pronounced segregation at intercellular regions, negatively impacting the overall mechanical integrity, especially elongation. Consequently, it is crucial to meticulously control manganese content within specified optimal ranges to maintain desirable microstructural and mechanical characteristics.

In summary, through controlled manganese additions up to 0.56%, this study successfully demonstrates the potential for achieving high-strength ductile iron while further reinforce the critical importance of controlling manganese levels, as excessive manganese content can adversely impact both microstructural uniformity and mechanical properties. So, from this study, we can utilized materials more comfortable with manganese up to 0.56% instead of 0.3% as usual.

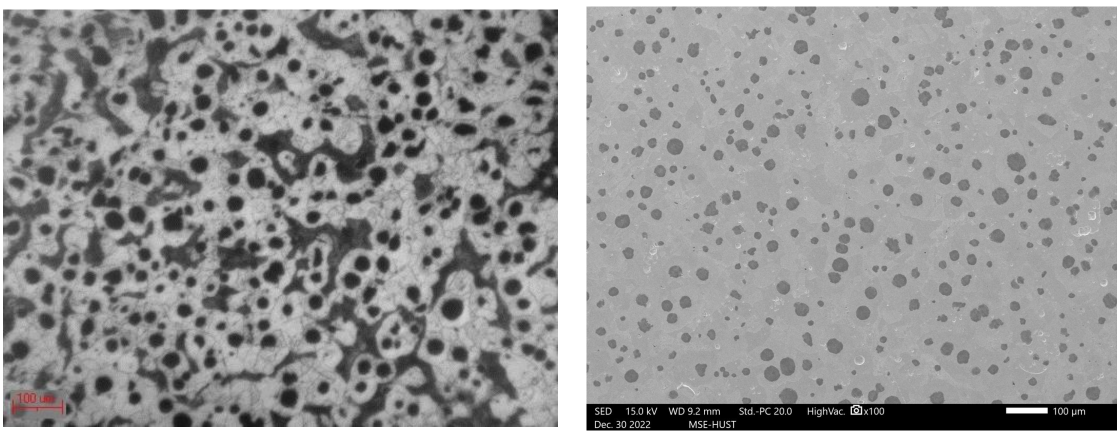
3.2 Mechanical properties

Figure 3 illustrates the mechanical properties as a function of increasing manganese content. A direct proportionality was observed between tensile strength and manganese content due to manganese's role in stabilizing pearlite. Specifically, tensile strength significantly increased with higher manganese contents due to enhanced pearlite phase formation, simultaneously resulting in a reduction in ductility and e

maintaining acceptable ductility and toughness. This broader compositional range significantly reduces dependency on specific high quality raw materials, thus lowering production costs and simplifying the casting process.

4 Conclusions

The present study demonstrates that the simultaneous addition of 0.4 wt.% inoculant and 1.2 wt.% nodulant enables the successful casting of ductile iron containing up to 0.56 wt.% manganese without compromising the target mechanical performance. Microstructural examination confirmed a fully spheroidal graphite morphology within a predominantly ferritic matrix, while tensile strength and elongation measurements met or exceeded the prescribed specifications. Moreover, the alloy's carbon equivalent of approximately 4.3 wt.% coincides with its eutectic composition, ensuring optimal fluidity during casting and excellent service behavior



a, Sample 4 with 0.53 % Mn   b, Sample 5 with 0.56% Mn

Figure 2. Microstructure of ductile iron with high manganese

under cyclic loading

Acknowledgments

This study caried out under the scheme collaboration between School of Materials Science and Engineering, Hanoi University of Science and Technology (HUST) and Song Cong Diesel Limited Company in Vietnam, named DISOCO (www.disoco.com.vn). Disoco company which is a member of Vietnam Engine & Agricultural Machinery Corporation (VEAM) is mainly casting of ductile cast iron along with somes hot forging and machining products. Annual exported to Europe, Asia, Africa over 40,000 ton. By using green sand and lost foam casting processes, Disoco can fabricated diversity intricated products with high precision and even for high pressure conditions

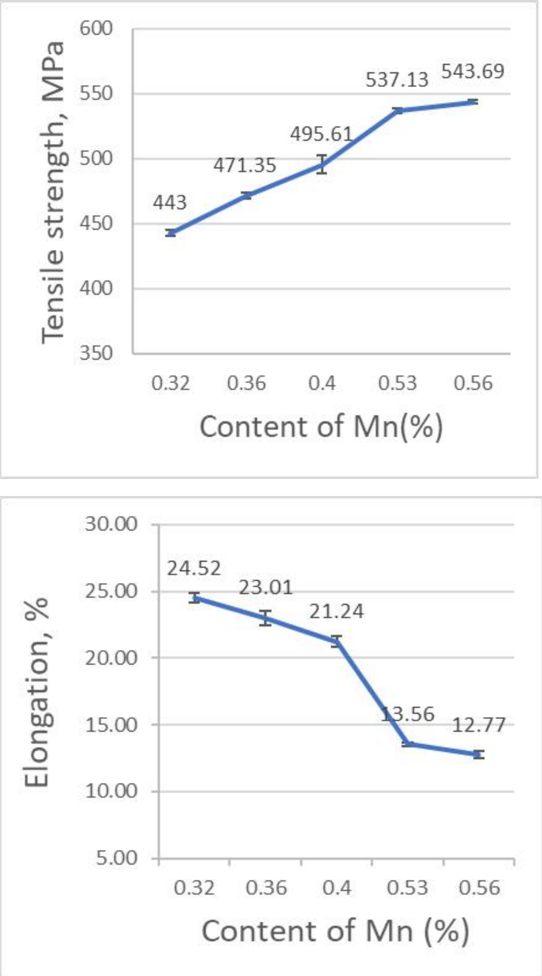


Figure 3. Mechanical properties

Conflicts of interest:

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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