EFFECT OF FTI-35 FERROTITANIUM MODIFICATION ON THE IMPACT TOUGHNESS AND TENSILE STRENGTH OF HADFIELD HIGH-MANGANESE STEEL

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Abstract - Modification is a widely used approach to improving the mechanical properties of alloys. This article investigates the modification of high-manganese steel—specifically, Hadfield steel—using ferrotitanium (FTi-35). In the experiments, particular attention was paid to incorporating titanium from ferrotitanium into the alloy and to its effect on the mechanical properties. Ferrotitanium was added to the charge at 0.4%, 0.6%, and 0.8%, and the influence of titanium on mechanical properties (impact toughness and tensile strength) was investigated. The samples were cast into sand–clay moulds. After casting, the specimens were machined to meet standard requirements. Impact toughness was measured using an MK-30A pendulum impact tester, and tensile strength was determined using an LFM-50 kN testing machine. Based on the experimental results, a relationship graph between titanium content and mechanical properties was developed. In addition, changes in the samples' microstructures and their correlation with mechanical properties were analysed. It was found that adding titanium refines the steel's grain structure, leading to a significant improvement in its mechanical properties.

Keywords: Hadfield steel, Ferrotitanium, Modification, Microstructure, Impact toughness, Tensile strength.

1. Introduction

The rapid development of mechanical engineering has led to increasingly stringent requirements for the performance of engineering components. Ferrous and non-ferrous alloys play an indispensable role across various industrial sectors, including mechanical engineering, the automotive industry, tractor manufacturing, aerospace engineering, shipbuilding, and many others [1–5]. Components for these industries are manufactured from these alloys using a variety of processing techniques, such as casting, metal forming, and rolling, depending on the intended application [6–9].

High-manganese steels are among the most important engineering materials, widely used in modern mechanical engineering, mining, metallurgy, and the transport industry. One of the most commonly used grades is 110G13L steel (GOST 21357-87), distinguished by its high impact toughness, excellent ductility, and superior wear resistance. The chemical composition of 110G13L steel typically includes 1.0–1.4 wt.% carbon and 11–14 wt.% manganese. The high manganese content stabilises the austenitic structure, which is responsible for the unique combination of mechanical and operational properties exhibited by this steel [10].

The principal advantage of high-manganese steels is their ability to work harden during service. Under dynamic loading and abrasive wear, the steel surface layer undergoes a significant increase in hardness, while the core retains its high toughness. Consequently, the material exhibits excellent resistance to both impact loading and severe abrasive wear. Owing to these outstanding

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characteristics, high-manganese steels are widely used to manufacture crusher jaws, mill liners, excavator bucket teeth, and other components operating under severe service conditions [11–13].

The mechanical and service properties of high-manganese steels depend not only on their chemical composition but also on the melting technology, casting conditions, cooling regime, and heat treatment parameters. Accordingly, considerable attention has recently been devoted to optimising the chemical composition, elucidating the mechanisms of alloying elements, and investigating the relationship between microstructure and mechanical properties of these steels. One of the most effective approaches to improving alloy performance is the addition of alloying and modifying elements [14–17].

Researchers worldwide have explored adding various alloying elements to steel to improve its mechanical properties. For instance, Li Z. and his team at Beijing University of Technology studied the development of β-phase titanium alloys, such as Ti-1023 and Ti-5553, using physical metallurgy modelling. This approach enabled them to design advanced structural materials with high elasticity and strong mechanical performance [18].

In addition, research groups led by Dierk Raabe at the Max Planck Institute for Sustainable Materials (formerly the Max-Planck-Institut für Eisenforschung) conducted fundamental studies using first-principles quantum-mechanical calculations to investigate the phase stability, elastic modulus, and thermodynamic behaviour of titanium-based alloys [19]. Their work established the relationship between phase transformations and the mechanical response of Ti–Nb and Ti–Mo alloy systems, enabling highly accurate predictions of their mechanical behaviour.

Published studies have reported that combining titanium and boron modifications of steels reduces the average martensite grain size from approximately 4.5 μm to 3.3 μm. This refinement increases the material's structural density, thereby improving ductility and wear resistance. These findings demonstrate that such modification techniques are applicable not only under laboratory conditions but also in large-scale industrial production.

Consequently, titanium-modified high-manganese steels are considered promising engineering materials for applications in structural engineering, mechanical manufacturing, mining, transportation, and the energy industry [19].

A brief analysis of the study by Bleck, W. indicates that the mechanical properties and deformation mechanisms of high-manganese steels are primarily governed by their stacking fault energy (SFE). Variations in SFE promote different deformation mechanisms, including Transformation-Induced Plasticity (TRIP), Twinning-Induced Plasticity (TWIP), and Microband-Induced Plasticity (MBIP). These mechanisms play a decisive role in determining the material's strength, ductility, and work-hardening capacity. The study also reported that the contents of manganese, carbon, and aluminium significantly influence both the stability of the austenitic phase and the SFE. While manganese and carbon stabilise the austenitic structure, aluminium increases the SFE, thereby altering the dominant deformation mechanisms. As a result, high-manganese steels can achieve a unique combination of high strength and excellent ductility [20].

The present study investigates the effect of adding FTi-35 ferrotitanium to 110G13L high-manganese steel on its microstructure and mechanical properties, specifically tensile strength and impact toughness. Furthermore, the optimal ferrotitanium addition required to achieve the best combination of mechanical properties for this steel grade is determined.

2. Materials and Methods

In this study, 110G13L high-manganese steel was selected as the experimental material. The chemical composition of the steel is presented in Table 1. Owing to its excellent combination of wear resistance, impact toughness, and work-hardening capability, this steel is widely used in the manufacture of heavy-duty industrial components. Typical applications include the housings of vortex and ball mills, crusher jaws and cones, excavator bucket teeth and front bucket walls, railway crossings, and other heavily loaded components operating under static and severe dynamic loading conditions, where high wear resistance and impact resistance are essential.

Table 1. Chemical composition of 110G13L high-manganese steel (%)

Fe	C	Si	Mn	Ni	S	P	Cr
~83	0.9-1.5	0.3 - 1	11.5 - 15	<1	<0.05	<0.12	< 1

In addition, FTi-35 ferrotitanium was selected as the modifier to introduce titanium into the steel composition [21]. Ferrotitanium is widely used in the steel industry, primarily as a deoxidising and alloying agent, improving steel cleanliness, refining the grain structure, and enhancing its mechanical properties.

The modification experiments were carried out using a DSP-6-I1 electric arc furnace (EAF). The DSP-6-I1 furnace is designed for melting carbon, quality, and alloy steels for ingot production. However, it can also be used to produce shaped castings. The furnace can be installed inside a sound-insulated enclosure and is manufactured in both left-hand and right-hand configurations.

In the left-hand configuration, the furnace transformer is located on the left side of the furnace. In contrast, in the right-hand configuration, it is positioned on the right when viewed from the metal-tapping side. The left-hand configuration is considered the standard design. The schematic structure of the electric arc furnace is shown in Figure 1.

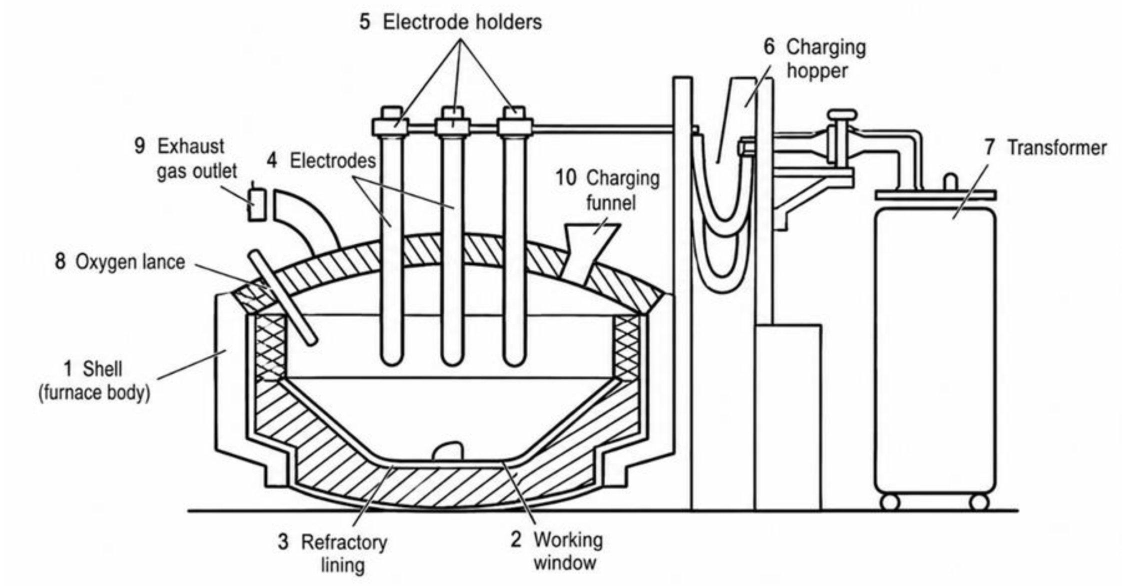

Figure 1: Schematic diagram of the DSP-6-I1 electric arc furnace

The tensile properties of the Ti-modified 110G13L steel were evaluated by uniaxial tensile testing on an LFM-50 kN universal testing machine manufactured by the Swiss company Walter + Bai AG, as shown in Figure 2.

Figure 2: LFM-50 kN universal tensile testing machine

In addition, the Charpy impact test was used to assess the specimens' resistance to dynamic loading. The energy absorbed during fracture was measured with a pendulum impact testing machine. Based on the experimental results, the impact toughness was calculated using the following equation [22]:

$$K = A / F$$

Where A is the impact energy absorbed during fracture (J) and F is the specimen's cross-sectional area (cm^2). The calculated impact toughness values were used to comprehensively evaluate the effect of titanium addition on the steel's mechanical performance.

The impact toughness of the specimens was evaluated at room temperature using an MK-30A pendulum impact testing machine, as shown in Figure 3. Standard Charpy V-notch specimens, measuring 10×10×55 mm and conforming to the Charpy test standard [23], were used for the impact tests.

In addition, the microstructure of the specimens was examined using a METAM PB-23 metallographic microscope. This microscope is designed for the visual observation of the microstructure of metals, alloys, and other opaque materials under reflected light. It enables microscopic examination using bright-field and dark-field illumination, as well as investigations under polarised light and differential interference contrast (DIC) microscopy. These capabilities provide detailed characterisation of the microstructural features of metallic materials.

Figure 3: LFM-50 kN universal tensile testing machine

3. Experimental

In the experiments, 110G13L high-manganese steel was modified by adding FTi-35 ferrotitanium in amounts corresponding to 0.4 wt.%, 0.6 wt.%, and 0.8 wt.% titanium relative to the charge. Initially, the steel was melted in an electric arc furnace. The ferrotitanium alloy was introduced by sprinkling it into the furnace both at the initial stage of charge melting and after the charge had completely melted. After the addition of the modifier, the molten alloy was held in the furnace for a predetermined period to ensure complete dissolution and homogeneous distribution of titanium throughout the melt.

The optimum pouring temperature was set at 1380–1410 °C, approximately 15 °C lower than the conventional casting temperature. This reduction in pouring temperature minimised casting defects, including surface burning, incomplete mould filling, gas porosity, and slag inclusions, during solidification.

After casting, the specimens were subjected to solution heat treatment at 1050–1150°C for 2.5 h to homogenise the chemical composition, reduce microsegregation generated during solidification, and dissolve undesirable secondary phases into the austenitic matrix. The selected solution treatment temperature ensured sufficient atomic diffusion, resulting in a more uniform distribution of alloying elements throughout the matrix. During the holding stage, titanium reacted with carbon to form fine and uniformly dispersed titanium carbide (TiC) precipitates. These thermally stable precipitates served as effective grain-boundary pinning particles, restricting austenite grain growth via the Zener pinning mechanism and promoting the formation of a refined, homogeneous austenitic microstructure [24]. Grain refinement is known to improve the mechanical performance of high-manganese steels by simultaneously increasing strength, toughness, and wear resistance. Following solution treatment, the specimens were immediately water-quenched to retain the high-temperature austenitic phase and to suppress the precipitation of undesirable carbides or phase transformations during cooling [25,26]. This heat-treatment procedure produced a stable, fully austenitic microstructure, providing a reliable basis for subsequent mechanical testing and microstructural characterisation. Following heat treatment, the specimens were machined to the required dimensions for mechanical testing [27].

The test specimens were prepared from cast bars measuring 400 mm in length and 40 mm in diameter using an NT-250I lathe. Standard dog-bone-shaped tensile specimens were machined with an overall length of 40 mm, a gauge diameter of 10 mm, a grip diameter of 15 mm, a gauge length of 25 mm, and grip section lengths of 7.5 mm, as illustrated in Figure 4.

Figure 4: Dog-bone-shaped tensile test specimens prepared for tensile strength testing.

Figure 5: Charpy impact test specimens prepared for impact toughness evaluation

In the next stage, prismatic specimens were prepared for impact toughness testing. The specimens had dimensions of 40 mm × 5 mm × 5 mm and contained a 1 mm-deep notch, as shown in Figure 5. All experimental tests were conducted in accordance with the relevant technical standards using calibrated and certified testing equipment.

4. Results

During tensile testing with the LFM-50 kN universal testing machine, the loading and deformation processes were continuously recorded using a digital controller. Proper specimen alignment prevented bending effects, and the maximum tensile strength was 400 MPa. The experimental results revealed a relationship between titanium content and the steel's tensile strength, shown in Figure 6.

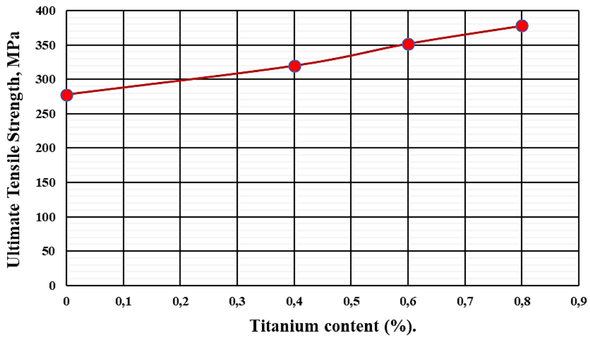

Figure 6: Effect of titanium content on the ultimate tensile strength of 110G13L steel

Based on the results presented in Figure 6, the effect of titanium addition on the ultimate tensile strength (UTS) of 110G13L high-manganese steel was investigated. This study involved modifying the steel with titanium additions of 0.4 wt.%, 0.6 wt.%, and 0.8 wt.% relative to the charge, followed by an evaluation of the tensile properties of the modified specimens.

The results showed that the unmodified alloy exhibited an ultimate tensile strength of 278 MPa, with the addition of 0.4 wt.% Ti, the tensile strength increased to 320 MPa. Increasing the titanium content to 0.6 wt.% further improved the tensile strength to 350 MPa, while the highest value of 378 MPa was obtained with 0.8 wt.% Ti. These results demonstrate a continuous increase in the ultimate tensile strength with increasing titanium content.

The improvement in tensile strength can be attributed to the grain-refining effect of titanium during solidification, which promotes a more homogeneous microstructure and facilitates the formation of strengthening phases. Consequently, the alloy exhibits greater resistance to plastic deformation, resulting in enhanced mechanical performance. The experimental results confirm that modifying 110G13L steel with titanium significantly improves its ultimate tensile strength, with the optimal performance among the investigated compositions achieved at a titanium content of 0.8 wt.%.

Subsequently, the impact toughness of the specimens was evaluated at room temperature using an MK-30A pendulum impact testing machine. Standard Charpy specimens with dimensions of 10 × 10 × 55 mm were used in accordance with the relevant testing standard. The principal technical characteristics of the MK-30A impact tester were examined before testing. The machine has a measuring range of 0–30 kg·m and a measurement accuracy of ±1%. Based on the experimental data, the relationship between titanium content and impact toughness was analysed, and the corresponding results are presented in Figure 7.

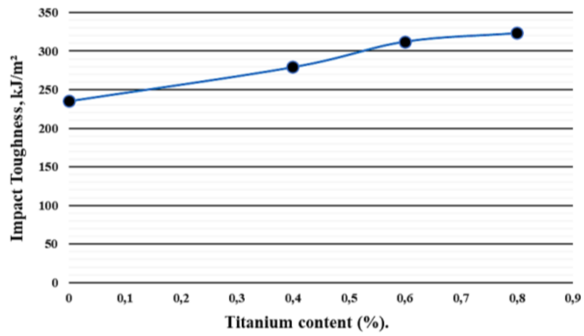

Figure 7: Relationship between titanium content and the impact toughness of Ti-modified 110G13L steel

Based on the experimental results, the effect of titanium addition on the impact toughness of 110G13L high-manganese steel was investigated, and the relationship between titanium content and impact toughness was established. As shown in Figure 7, the impact toughness increased consistently with increasing titanium content. The unmodified alloy exhibited an impact toughness of 235 kJ/m^2. When 0.4 wt.% Ti was added the impact toughness increased to 278 kJ/m^2. Further increasing the titanium content to 0.6 wt.% resulted in an impact toughness of 311 kJ/m^2, indicating a significant improvement in the alloy's resistance to dynamic loading. The highest value, 322 kJ/m^2, was obtained for the specimen containing 0.8 wt. % Ti.

The improvement in impact toughness can be attributed to the grain-refining effect of titanium during solidification. Titanium increases the number of heterogeneous nucleation sites, leading to grain refinement, while the formation of titanium carbides and nitrides contributes to both microstructural strengthening and enhanced toughness. As a result, the material absorbs impact energy more effectively and exhibits greater resistance to brittle fracture.

As shown in Figure 7, the rate of increase in impact toughness was more pronounced up to 0.6 wt.% Ti. However, the impact toughness continued to increase at 0.8 wt.% Ti, the rate of improvement became less significant, suggesting a tendency toward saturation. Nevertheless, within the investigated composition range, titanium addition consistently improved the alloy's impact toughness, with the highest value achieved at 0.8 wt.% Ti.

In the next phase of the research, the microstructures of the specimens were analysed. Prior to microscopic examination, the specimens were mechanically prepared and polished using a NERIS grinding and polishing machine. They were then chemically etched and examined under a METAM PB-23 metallographic microscope. The metallographic micrographs of the specimens are shown in Figure 8.

The microstructural analysis presented in Figure 8 confirms that titanium modification significantly influences the microstructure of 110G13L high-manganese steel. In the unmodified specimen (Figure 8a), coarse austenitic grains with clearly defined grain boundaries were observed. Dark carbide phases and non-metallic inclusions were distributed non-uniformly throughout the microstructure, indicating considerable microstructural heterogeneity. Such a heterogeneous microstructure adversely affects the mechanical and service properties of the steel, particularly its impact toughness and tensile strength.

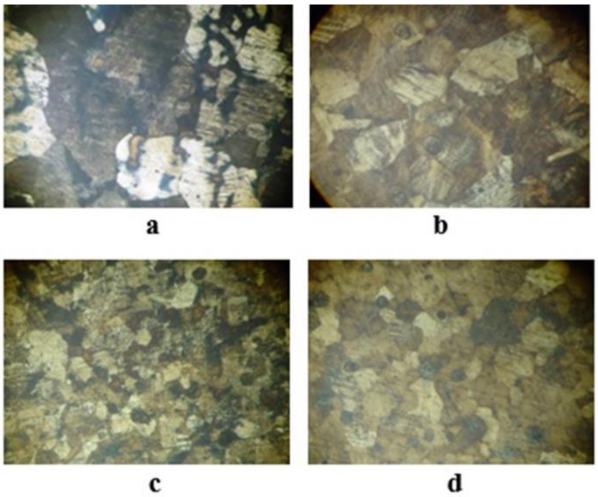

Figure 8: Microstructures of 110G13L steel: (a) without Ti addition; (b) with 0.4 wt.% Ti; (c) with 0.6 wt.% Ti; and (d) with 0.8 wt.% Ti

When 0.4 wt.% Ti was added (Figure 8b), noticeable grain refinement of the austenitic matrix was observed. Compared with the unmodified specimen, the grains became considerably finer and more uniformly distributed. This behaviour can be attributed to the formation of TiC and TiN particles during solidification, which act as heterogeneous nucleation sites. Consequently, grain growth is effectively suppressed, resulting in a more homogeneous microstructure.

At a titanium content of 0.6 wt.% (Figure 8c), the microstructure exhibited the finest and most uniform grain morphology. The austenitic grains were significantly refined, while carbide particles and secondary phases were dispersed uniformly throughout the matrix as fine precipitates. These observations indicate that titanium modification was most effective at this composition. According to the Hall–Petch relationship, grain refinement directly increases steel strength by impeding dislocation motion [28, 29].

When the titanium content was further increased to 0.8 wt.% (Figure 8d), the alloy retained its fine-grained microstructure. However, localised regions containing larger concentrations of dark precipitates were observed. This behaviour is attributed to the increased formation of TiC and TiN particles resulting from the higher titanium content. Consequently, the microstructural homogeneity was slightly lower than that observed in the specimen containing 0.6 wt.% Ti, although the grain refinement remained superior to that of the unmodified alloy.

5. Discussions

Hadfield high-manganese steel is widely used in the mining, railway, and construction industries due to its excellent work-hardening capability, high impact toughness, and outstanding wear resistance. However, the coarse austenitic grains formed during conventional casting limit important mechanical properties, particularly tensile strength and impact toughness. Therefore, numerous studies have focused on refining the microstructure through alloy modification to improve the mechanical performance of this steel.

Venturelli et al. reported that modification with hafnium reduced the average austenite grain size from approximately 3000 μm to 600 μm. As a result, the ultimate tensile strength increased by approximately 37%, while the Charpy impact toughness improved by 15%. The authors attributed these improvements to a refined austenitic grain structure, enhanced work-hardening behaviour, and a more uniform distribution of deformation under applied loading [30]. Titanium has also been extensively investigated as a microalloying element for Hadfield steel. Previous studies have demonstrated that titanium forms stable Ti(C, N) precipitates that act as heterogeneous nucleation sites during solidification and effectively inhibit the growth of austenite grains [31]. Furthermore, Bańkowski et al. investigated the effect of magnesium modification on Hadfield high-manganese steel and reported that magnesium effectively refines the austenitic grain structure and improves the impact toughness by reducing the amount of non-metallic inclusions [32]. Additionally, Lindroos et al. thoroughly studied the deformation behaviour, strain-hardening, and wear mechanisms of chromium-alloyed Hadfield steel under abrasive and impact loads. Their findings showed that the addition of chromium greatly enhances the steel's resistance to abrasive wear while maintaining its superior strain-hardening properties during use [33].

In contrast to prior research, the present study investigates the modification of Hadfield steel through the addition of FTI-35 ferrotitanium. Unlike pure titanium, FTI-35 is an industrially feasible ferroalloy that can be incorporated directly into molten metal during melting. The experimental results demonstrate that titanium introduced through FTI-35 significantly enhances both impact toughness and tensile strength by refining the austenitic grain structure and promoting the formation of fine titanium-containing particles. The optimum titanium addition produced the most homogeneous microstructure and the best combination of mechanical properties. These findings not only confirm the conclusions of previous studies but also demonstrate the practical effectiveness of FTI-35 ferrotitanium in modifying 110G13L Hadfield high-manganese steel under industrial casting conditions.

Overall, the experimental study demonstrates that modification of 110G13L high-manganese steel with FTi-35 ferrotitanium effectively refines the microstructure and improves its mechanical properties. Therefore, the modified alloy is a promising material for producing cast components that operate under severe service conditions.

The potential applications of the developed material include heavy-duty cast components for mining machinery, construction and mechanical engineering equipment, crushers, excavators, grinding mills, railway components, and other wear-resistant engineering products operating under severe impact and abrasive wear conditions. Since these cast components are continuously exposed to intense abrasive wear and repeated impact loading in service, using titanium-modified high-manganese steel can significantly enhance their operational performance. Compared with conventional unmodified high-manganese steels, titanium modification refines the microstructure and improves wear resistance and impact toughness, thereby extending component service life, reducing maintenance frequency, minimising replacement costs, and increasing the overall reliability and durability of equipment operating in harsh industrial environments.

6. Conclusions

Following the experimental investigations, the subsequent conclusions can be delineated.

Modifying 110G13L high-manganese steel with titanium significantly refines the austenitic grain structure and improves microstructural homogeneity. During solidification, titanium forms TiC and TiN particles, which serve as heterogeneous nucleation sites and effectively inhibit austenite grain growth. Consequently, the steel's mechanical properties are significantly enhanced.

Titanium modification increased the alloy's ultimate tensile strength by approximately 25–28%, while impact toughness improved by approximately 29–33% compared with the unmodified steel. These improvements are attributed to grain refinement and the more uniform distribution of strengthening phases within the microstructure.

Microstructural analysis revealed that the specimen containing 0.6 wt.% Ti exhibited the most refined and homogeneous austenitic structure, characterised by the finest grain size and the most uniform distribution of secondary phases. This composition can therefore be regarded as the optimum titanium content for achieving the most favourable microstructural characteristics in 110G13L high-manganese steel.

Overall, the results demonstrate that FTi-35 ferrotitanium is an effective modifier that improves the microstructure and mechanical performance of 110G13L high-manganese steel, making it a promising material for manufacturing wear-resistant cast components for severe service conditions.

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