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STUDY ON THE INFLUENCE OF MECHANICAL PROPERTIES OF MALLEABLE CAST IRON VIA NICKEL MODIFICATION

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Abstract - This study investigates the modification process of malleable cast iron, an iron–carbon alloy, using nickel as a modifying element. In the experiments, nickel was added to the charge in amounts of 0.1%, 0.3%, and 0.5% by weight, and its effect on the mechanical properties—hardness, impact toughness, and tensile strength—was examined. Initially, nickel was introduced into white cast iron, and the molten alloy was cast into sand–clay molds. The obtained cast samples were then subjected to heat treatment to produce malleable cast iron. The mechanical properties of the samples were evaluated using standard testing methods. In addition, changes in the microstructure of the samples were analyzed. The results showed that nickel modification positively influences graphite formation in cast iron while suppressing the formation of cementite (Fe_3C). As a result, the microstructure of the samples became more stable and homogeneous, leading to an improvement in mechanical properties.

Keywords: Cast iron, Hardness, Impact toughness, Tensile strength, Modification, Low-temperature heat treatment, Mechanical properties.

1. Introduction

Cast iron, an iron–carbon alloy, is one of the most widely used engineering materials due to its favorable combination of strength, ductility, and impact toughness [1,2]. It is produced by heat treatment of white cast iron, during which brittle cementite structures are transformed into more stable ferritic or pearlitic matrices containing temper carbon nodules. This transformation significantly improves its mechanical properties and enables its application in various industrial fields, including automotive components, agricultural machinery, and structural elements [3–5].

In modern materials science, improving the mechanical properties of cast irons remains one of the key research directions. Alloy modification is considered one of the most widely used approaches for enhancing mechanical performance [6–9]. Among various methods, alloying and modification with elements such as nickel (Ni) have demonstrated effective results. Nickel is known to refine the microstructure, stabilize austenite, and promote a more uniform distribution of carbon particles within the matrix, thereby improving strength, hardness, and toughness.

Furthermore, the addition of nickel influences phase transformations, reduces brittleness, and consequently enhances both impact toughness and tensile strength. In addition, nickel-modified malleable cast iron exhibits improved wear and corrosion resistance, which broadens its applicability under severe service conditions.

To date, numerous studies on cast iron have been conducted by researchers worldwide. For instance, Taiwanese researchers S. S. Shieh and his colleagues have investigated in detail the tensile properties of austempered ductile iron (ADI) with a high bainitic structure derived from nodular cast iron over a temperature range from 27 °C to 420 °C [10].

Their results indicate that with increasing austenitizing and austempering temperatures, the stress values of the material exhibit a decreasing trend. The researchers classified the tensile behavior

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into two main temperature regions. In the low-temperature region, dynamic strain aging associated with the ferrite phase predominates. In the high-temperature region, a reduction in tensile properties is observed due to the formation of quasi-continuous carbide particles originating from austenite.

Moreover, it was determined that ADI samples with the finest microstructure did not exhibit instability in the deformation process during mechanical testing. This finding demonstrates that controlling the microstructure can significantly improve the mechanical properties of the material.

For malleable cast iron, studies conducted by Fatik Hayati Çakır [11] have demonstrated that the austempering process can markedly improve its mechanical properties, particularly impact toughness. Furthermore, investigations by M. V. Riabov and co-authors [12] evaluated the impact behavior of various grades of austempered ductile iron (ADI) at sub-zero temperatures, with comparative analysis against conventional ferritic grade 60-40-18 and pearlitic grade 100-70-03 ductile irons.

The results revealed that for all ADI grades, impact toughness decreases with decreasing austenite content and testing temperature. However, in ADI grade 5, which contains a lower amount of austenite, the reduction in impact toughness was relatively less pronounced. The samples were prepared without a notch in accordance with the ASTM International E-23 standard, and the tests were conducted at room temperature as well as at −40 °C and −60 °C.

In another study, S. E. Kisakurek and A. Ozel investigated the influence of various factors on the energy absorption properties of five cast samples made of ductile iron conforming to the EN 1563 standard under dynamic loading conditions. The main objective of the study was to determine how different heat treatment processes, particularly austempering and pearlite–ferrite transformations, affect the impact properties of these cast materials at sub-zero temperatures.

The results showed that the austempering process, specifically the transformation of austenite into bainite, has a negative effect on the impact properties of ferritic cast samples at low temperatures. This indicates that austempering does not improve the energy absorption capacity of these materials under such conditions. On the other hand, pearlite–ferrite cast irons demonstrated a significant improvement in energy absorption properties. This phase transformation positively affects impact performance at low temperatures, making these materials more suitable for applications requiring high energy absorption [13].

The aim of the present study is to investigate the effect of nickel addition on the mechanical properties of malleable cast iron, with particular emphasis on hardness, impact toughness, and tensile strength. During the research, samples containing different amounts of nickel are prepared, their microstructures are analyzed using metallographic methods, and their mechanical properties are evaluated based on standard testing procedures. The results of this study are expected to contribute to the development of cast iron materials with enhanced properties and improved performance for industrial applications.

2. Materials and Methods

The production of malleable cast iron is a complex, multi-stage technological process consisting of two fundamentally interconnected stages: (i) the production of white cast iron castings with strictly controlled chemical composition, and (ii) subsequent graphitizing annealing [14]. The chemical composition of the malleable cast iron employed as the experimental material in this study is presented in Table 1.

In the experiments, the samples were first modified with nickel and cast into sand–clay molds [15]. Nickel was added to each sample in amounts of 0.1%, 0.3%, and 0.5% relative to the charge, and the modified samples were obtained through casting. The cast samples were then subjected to heat treatment, during which white cast iron was transformed into malleable cast iron.

Table 1. Chemical composition of malleable cast iron (%).

Fe	C	Si	Mn	P	S	Other elements
95.2	2.5	1.3	0.5	0.02	0.04	0.43

To obtain malleable cast iron with a maximum number of graphite inclusions, a low-temperature treatment method of white cast iron was employed, also referred to as artificial aging [16]. The study investigated the effect of temperature and duration of low-temperature treatment on the quantity of graphite inclusions in cast iron.

At the first stage of graphitization, the castings were heated in a muffle furnace to a relatively low temperature in the range of 300–400 °C and held for 5–10 hours in order to create the most favorable conditions for the formation of graphite inclusions. This is explained by the relatively low rate of diffusion processes, which has a positive effect on the structure of cast iron.

After the low-temperature treatment, the samples were subjected to normal cooling in the furnace down to room temperature (23°C) (Figure 1).

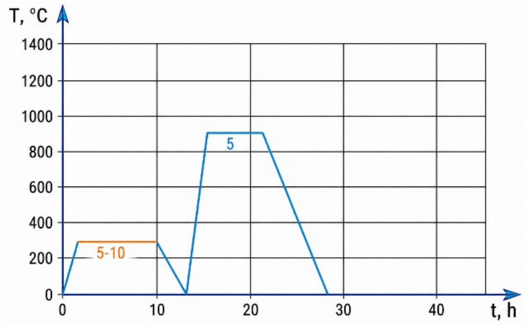


Figure 1: Schematic illustration of the annealing process of white cast iron using low-temperature treatment.

After the completion of the primary stage of graphitization, the cooled samples were transferred to a preheated furnace at 950 °C to ensure the formation of a saturated γ-solid solution with the corresponding dissolution of carbides in accordance with the Fe–C phase diagram. Subsequently, the castings were held within the temperature range of 940–960 °C for 5 hours, allowing graphitization to proceed at a constant temperature until the complete disappearance of carbides. This process ensured that the structure of the cast iron consisted of austenite (of stable composition) and graphite.

At the same time, partial decarburization of austenite was expected, as austenite at the heat treatment temperature may contain approximately 1.4–1.7 wt.% carbon in solid solution. Further holding at this temperature did not produce significant changes, except for homogenization of composition and stabilization of the phase constituents of the cast iron structure.

After achieving the austenitic phase during holding, the castings were furnace-cooled to room temperature at a rate not exceeding 55 °C/h. This controlled cooling was applied to ensure that not all carbon remained dissolved in austenite, allowing part of it to diffuse toward the surface of the material.

In the subsequent stage of the experiments, the mechanical properties of the heat-treated samples were investigated. Standard specimens were prepared for mechanical testing to determine hardness, impact toughness, and tensile strength in accordance with relevant standards.

Impact bending tests were performed using a Charpy impact test setup, specifically a pendulum impact tester (Figure 2). The method is based on the fracture of a notched specimen subjected to a single blow from a pendulum hammer (striker). The specimen is supported on anvils, and upon impact, the absorbed fracture energy (impact energy) is determined. The impact toughness is subsequently calculated as the ratio of the absorbed energy to the cross-sectional area beneath the notch.

Figure 2: Pendulum impact tester.

Hardness measurements were performed using the Brinell hardness test in accordance with ISO 6506-1:2015. Polished specimen surfaces were prepared to ensure a smooth, flat contact area for accurate indentation using a 10 mm diameter spherical indenter.

Prior to polishing, a portion of the material was cut from the prepared casting or specimen for subsequent testing. The cut samples, containing different nickel contents, had dimensions of 5 × 50 mm in width and length, with a thickness of 5 mm. The sample obtained by casting for hardness determination is shown in Figure 3 below.

Figure 3: Specimen for hardness testing.

After the preparation and cutting of the specimens for Brinell hardness testing, manual surface grinding was carried out to obtain a flat and smooth surface. The grinding process was performed using abrasive papers of varying grit sizes, ranging from P80 to P1200. This procedure was intended to eliminate surface irregularities and to ensure reliable contact between the specimen surface and the indenter.

Tensile tests were carried out using a WDW-100E universal testing machine with a maximum load capacity of 100 kN (Figure 4). Strain measurements were performed using foil-based strain gauge sensors with electrical resistance. The sensors were calibrated for testing at room temperature.

After the specimens were securely fixed in the gripping device, the tensile test was initiated with a controlled increase in load (force). During the test, the applied load increased uniformly, leading to a proportional increase in tensile stress, which attained a peak value of 30 MPa.

Figure 4: WDW-100E universal tensile testing machine.

3. Results and Discussions

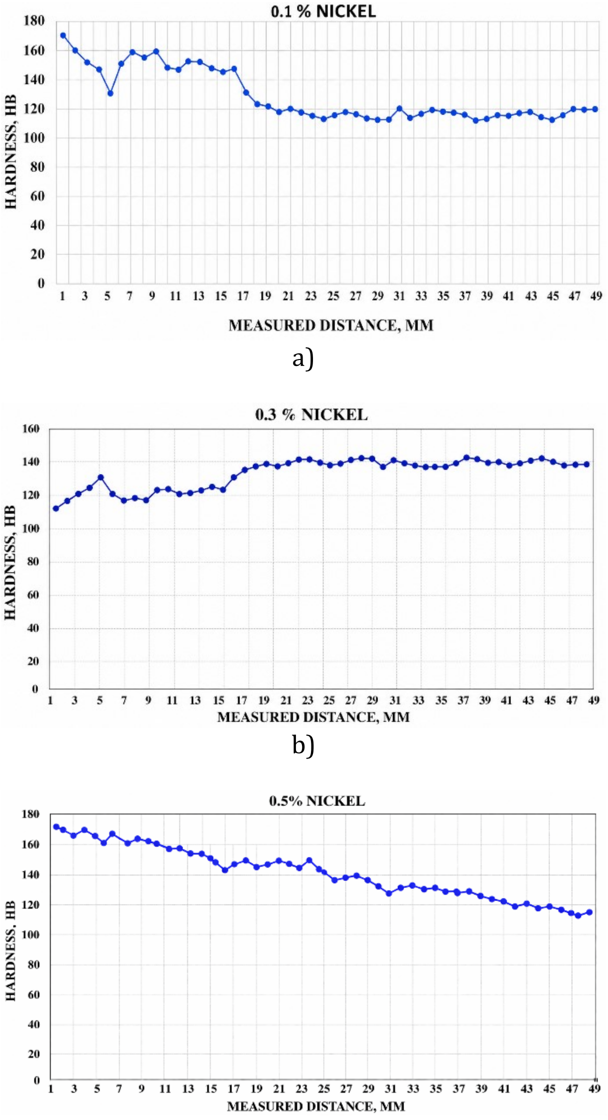
The hardness of the mechanically processed samples was measured. The measurement step was set to 1 mm to ensure high data accuracy and to minimize possible experimental errors (Figure 5).

Based on the obtained data, it can be concluded that with increasing nickel content in malleable cast iron, the hardness increases proportionally with its concentration. At an addition of 0.1 wt.% Ni, the average hardness value based on 49 measurements was 127.77 HB with a deviation of ±9.28. For the alloy containing 0.3 wt.% Ni, the average hardness reached 135.89 HB with a deviation of ±16.54, while at 0.5 wt.% Ni, the hardness increased to 157.49 HB with a deviation of ±8.54.

A common trend was observed in all samples: the hardness at the outer surface was higher compared to the middle and end regions of the specimens (Figure 5). This may be attributed to the fact that the modifier exhibits a more pronounced effect on the surface layer of the material.

The results given in figure 5 indicate that the hardness of the cast iron increases with increasing nickel (Ni) content. This can primarily be attributed to the dissolution of nickel into the iron matrix, leading to solid solution strengthening, which restricts dislocation motion. In addition, the incorporation of Ni promotes an increase in the pearlite phase fraction, which is inherently harder than ferrite, thereby contributing to the overall increase in hardness. Furthermore, nickel facilitates grain refinement, resulting in a more compact and denser microstructure. The higher hardness observed at the surface regions of the samples can be explained by the higher cooling rate in these areas, which leads to the formation of a finer and harder microstructure. Therefore, the increase in hardness is the combined effect of the structural and phase transformations induced by nickel addition.

In the next stage, tensile strength tests were carried out. After the specimens were securely fixed in the gripping device, the tensile loading process was initiated with a gradual increase in load. During the test, a uniform increase in load was observed, reaching up to 30 MPa. Figure 6 shows the stress–strain curves of malleable cast iron modified with different nickel contents.



a)

b)

c)

Figure 5: Hardness as a function of nickel concentration: (a) 0.1%, (b) 0.3%, and (c) 0.5%.

Based on the obtained data, it can be concluded that increasing the nickel content from 0.1 to 0.5 wt.% results in a monotonic increase in ultimate tensile strength and a moderate rise in the yield strength of malleable cast iron. The yield strength increases from 11 kgs/mm^2 to 28–30 kgs/mm^2, indicating a significant strengthening effect of nickel.

The ductility changes only slightly, remaining within the range of 0.1–0.3% (Figure 6.).

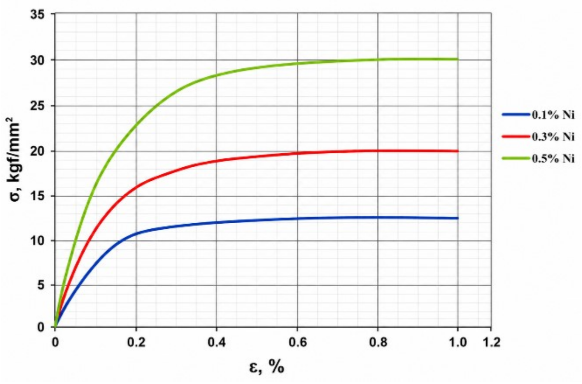


Figure 6: Stress–strain curve.

At a nickel content of 0.5 wt.%, the maximum strengthening effect is achieved while preserving the characteristic shape of the tensile curve typical for malleable cast iron. This indicates the full realization of the modification potential of nickel at this concentration. For impact toughness testing, a standard first type of U-notched specimen was selected (Figure 7). The specimens were placed on the supports of the pendulum impact tester so that the notch faced in the direction opposite to the impact. The positioning of the notch was carried out symmetrically with respect to the supports using a template.

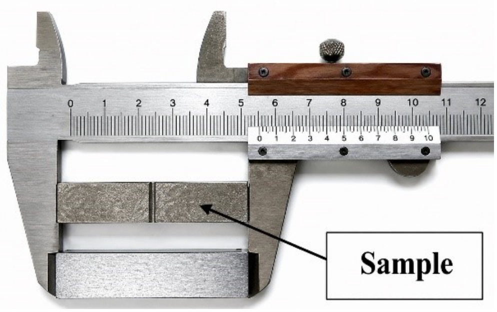


Figure 7: Specimens for Charpy impact testing.

The impact energy was determined using a pendulum impact tester, where the measurement process was carried out automatically. After each test, the results were recorded and accurately evaluated using the computer software integrated with the testing system. The main measured parameter was the absorbed energy (K), which represents the work required to fracture the specimen, corrected for frictional losses. After the measurements, the obtained values of impact toughness were recorded in Table 2 for further analysis.

Table 2. Results of impact bending tests of malleable cast iron (according to ASTM E23-16b)

Sample No.	Melt No.	Impact toughness (J/cm^2)
1	I (0.1% Ni)	39
2	I (0.1% Ni)	38
3	II (0.2% Ni)	39
4	II (0.2% Ni)	43
5	III (0.3% Ni)	46
6	III (0.3% Ni)	48
7	III (0.3% Ni)	45
8	IV (0.4% Ni)	46
9	IV (0.4% Ni)	49
10	IV (0.4% Ni)	47
11	V (0.5% Ni)	51
12	V (0.5% Ni)	47

During the investigation of nickel concentration in the alloy, five melts were produced with corresponding compositions ranging from 0.1 to 0.5 wt.% Ni. The experimental results showed that the average impact toughness of malleable cast iron at a temperature of 20 ± 3 °C was 24 J/cm^2, which meets the requirements of GOST 1215-79 for this grade (not less than 20 J/cm^2).

The results confirm that the investigated batch of cast iron possesses sufficient ductility and impact toughness, ensuring its applicability for components operating under dynamic loading conditions. Further increase in nickel content does not lead to an improvement in impact toughness; instead, it deteriorates the mechanical properties, as also reported in other studies [17-21].

The addition of nickel in the range of 0.3–0.4 wt.% provides the highest values of impact toughness. Increasing the nickel concentration beyond 0.5 wt.% results in a decrease in impact toughness, which is likely associated with the formation of harder but less ductile structural constituents (table 2).

After the mechanical testing of the specimens, their microstructural analysis was carried out. A metallographic method was employed to investigate the internal structure of the modified malleable cast iron, addressing the presence of crystals, their size, and inclusions within the material. After thorough cleaning to remove surface contaminants, the specimens were mounted in plastic molds and embedded in liquid resin for subsequent preparation and analysis.

The examination of the microstructure was performed using chemical etching with a 3% nital solution [22]. The nital reagent was prepared using 99% ethyl alcohol, nitric acid (HNO_3, 60%), distilled water, and sodium hydroxide (NaOH).

Figure 8 shows the microstructure of malleable cast iron with different nickel contents (a–c). The microstructural observations clearly indicate that nickel plays a significant role in modifying phase distribution and refining the grain structure.

In Figure 8(a), corresponding to lower nickel content, the structure is characterized by relatively coarse grains and the presence of irregular graphite particles dispersed within a ferritic/pearlitic matrix. Localized dark regions may indicate residual cementite or non-uniform graphitization, suggesting incomplete suppression of carbide phases.

As illustrated in Figure 8(b), an increase in nickel content leads to a more uniform microstructural arrangement. The graphite particles appear more evenly dispersed throughout the matrix, accompanied by a noticeable refinement of the grain structure. In addition, the diminished presence of carbide-like phases suggests that nickel plays a significant role in inhibiting the formation of cementite (Fe_3C) during both solidification and subsequent heat treatment processes.

In Figure 8(c), at higher nickel content, a well-developed and refined microstructure is observed. The grains are finer and more equiaxed, and graphite is more spheroidized and evenly distributed within the matrix. This refinement is associated with improved phase stability and enhanced diffusion during graphitizing annealing.

From a mechanistic standpoint, nickel acts as an austenite stabilizer, increasing the stability range of γ-phase and widening the eutectic transformation interval between γ–graphite and γ–Fe_3C. As a result, the formation of cementite is thermodynamically and kinetically suppressed, promoting graphitization and preventing the development of white cast iron structures.

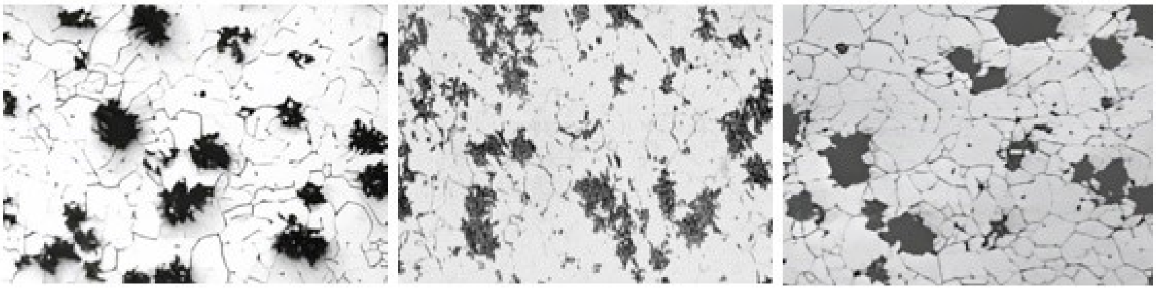

(a) *(b)* *(c)*

Figure 8. Microstructure of malleable cast iron: (a) 0.1% Ni, (b) 0.3% Ni, and (c) 0.5% Ni.

Overall, the results confirm that increasing nickel content enhances microstructural uniformity, promotes grain refinement, and suppresses carbide formation, which is consistent with improved mechanical performance observed in alloyed malleable cast irons.

Based on the nickel modification technology investigated in this study, such materials can be effectively applied in mechanical engineering for components operating under high loads and dynamic conditions (such as gears, shaft elements, and bearing parts), in the automotive industry for engine and transmission components, as well as in agricultural and heavy machinery. Furthermore, due to their improved structural stability and enhanced wear resistance, their use is highly efficient in structures requiring long-term service performance.

4. Conclusions

In this study, the effect of nickel (Ni) addition on the mechanical properties of malleable cast iron was comprehensively investigated. Based on the experimental results, the following main scientific conclusions were obtained.

First, the hardness results showed that increasing nickel content leads to a significant improvement in hardness. Specifically, at 0.1 wt.% Ni, the average hardness was 127.77 HB; at 0.3 wt.% Ni, it increased to 135.89 HB; and at 0.5 wt.% Ni, it reached 157.49 HB. These results indicate the high efficiency of nickel as a strengthening element. Additionally, it was observed that the hardness at the surface of all samples was higher than in the central regions, which can be explained by the more pronounced effect of the modifier in the surface layer.

Second, the tensile test results demonstrated that the strength of the material increases with increasing nickel content. The yield strength increased from 11 kg/mm^2 to 28–30 kg/mm^2. This indicates that while nickel enhances the strength of the material, it does not significantly deteriorate its ductility.

Third, the impact toughness results revealed that the optimal performance is achieved within the range of 0.3–0.4 wt.% Ni. In this interval, the material maintains a favorable balance between strength and ductility. However, increasing the nickel content beyond 0.5 wt.% may lead to a decrease in impact toughness, despite the increase in hardness. This is likely associated with excessive hardening of the structure and the formation of brittle phases.

Fourth, metallographic analysis confirmed that nickel addition positively influences graphite formation and suppresses the formation of cementite (Fe_3C). As a result, the microstructure becomes more stable and homogeneous, which contributes to the improvement of mechanical properties. Nickel also extends the eutectic transformation interval, thereby limiting the formation of white cast iron structures.

Overall, the results of this study demonstrate that modification of malleable cast iron with nickel significantly improves its mechanical properties. The most optimal results were obtained in the range of 0.3–0.4 wt.% Ni, which can be considered the most suitable composition for practical industrial applications.

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