International Journal of
Structural Engineering and Analysis
https://journalspub.com/journal/ijsea/

ISSN: 2456-5326
Volume 11, Issue 2, 2025
July-December
DOI (Journal): 10.37628/IJSEA

Research IJSEA

Analysis of Effect Due to Various Heat Treatment Processes on Morphological and Microstructural Properties of Grey Cast Iron

Sunil Kumar Singh[1,*], Deepak Agarwal[2], Anurag Singh[2]

Abstract

Grey cast iron, a member of the cast iron family, is defined by the presence of flake graphite in its composition. It displays distinct qualities encompassing strength, hardness, modulus of elasticity, shock absorption, wear resistance, and thermal conductivity. Particularly noteworthy is its exceptional performance in casting, cutting abilities, and its cost-effective casting process. Its primary utilization occurs predominantly within industries, where its durability and adaptable attributes find purpose. The pivotal element influencing its distinctive properties lies in the inclusion of microstructural flake graphite. Cracking is a widespread occurrence that extends across industries, various domains, and research undertakings. Currently, understanding the behavior of cracks holds paramount importance in enhancing product longevity. Contemporary ongoing research centers on a meticulous analysis of the crack characteristics of grey cast iron, utilizing a diverse range of heat treatment methodologies.

Keywords: As-cast ductile iron, annealing, hardening and tempering, microstructure, tension test

INTRODUCTION

Grey cast iron, an integral member of the cast iron family, stands as a testament to the profound synergy between metallurgy, engineering, and industry. This versatile material has traversed centuries of technological evolution, shaping the very foundation of modern infrastructure, transportation, and manufacturing. Its distinctive attributes, ranging from microstructural composition to mechanical properties, have propelled it to a position of paramount importance in diverse applications across various sectors [1].

Its renowned prevalence in industrial contexts can be attributed to its exceptional amalgamation of strength, resistance to wear, thermal conductivity, and dampening capabilities. What sets grey cast iron apart is its distinct microstructure, characterized by the presence of flake graphite, which imparts these exceptional traits, differentiating it from other variants of cast iron [2].

In this comprehensive exploration, the research embarks on an in-depth journey into the world of grey cast iron, unraveling its historical significance, microstructural intricacies, mechanical behavior, processing methodologies, industrial applications, challenges, and prospects.

The roots of grey cast iron can be traced back to antiquity, where it emerged as a pivotal advancement in the utilization of iron. The earliest civilizations recognized its potential, harnessing its superior strength and durability for architectural

***Author for Correspondence**
Sunil Kumar Singh
E-mail: lkosunil.singh@gmail.com

[1]M. Tech. Scholar, Department of Mechanical Engineering, Institute of Engineering and Technology, Dr. Ram Manohar Lohia Avadh University, Faizabad, Uttar Pradesh, India
[2]Assistant Professor, Department of Mechanical Engineering, Institute of Engineering and Technology, Dr. Ram Manohar Lohia Avadh University, Faizabad, Uttar Pradesh, India

Received Date: April 23, 2025
Accepted Date: August 22, 2025
Published Date: August 12, 2025

Citation: Sunil Kumar Singh, Deepak Agarwal, Anurag Singh. Analysis of Effect Due to Various Heat Treatment Processes on Morphological and Microstructural Properties of Grey Cast Iron. International Journal of Structural Engineering and Analysis. 2025; 11(2): 16–31p.

elements, tools, and weaponry. However, it was during the Industrial Revolution that grey cast iron truly came into its own [3, 4]. The advent of more efficient production methods, such as coke-fueled blast furnaces and improved casting techniques, enabled the mass production of cast iron products. This marked the material's transition from artisanal applications to a foundational material in the burgeoning industrial landscape [5].

Grey cast iron's captivating attributes are intimately linked to its complex microstructure. Comprising a matrix of ferrite, pearlite, and other constituents, its defining characteristic is the presence of flake graphite. The interplay between these phases gives rise to its unique combination of mechanical properties, thermal conductivity, and damping capabilities [6, 7]. The formation and distribution of graphite flakes within the iron matrix govern its macroscopic behavior, making a thorough understanding of its microstructural composition crucial for optimizing its performance [8].

The intricate relationship between the microstructural composition of grey cast iron and its mechanical performance across various conditions is a central focus. The dispersion of flake graphite within a matrix of ferrite and pearlite contributes to its exceptional ease of machining, stability in thermal conditions, and capacity for dampening vibrations. This microstructural configuration not only shapes the macroscopic attributes of grey cast iron but also plays a pivotal role in dictating its response to diverse processing methodologies, heat treatments, and load-bearing situations [9].

The adaptability and versatility inherent in grey cast iron have resulted in its diverse implementation across a multitude of industries, spanning automotive components and machinery elements to culinary utensils and construction materials. Its advantageous cost-to-performance ratio further reinforces its pivotal role as a favored material in various engineering applications [10].

However, despite its widespread utility, a persistent drive exists to fine-tune and customize its characteristics to meet specific requirements. This impetus propels ongoing research initiatives encompassing areas such as alloying, heat treatment, and microstructural engineering [11, 12].

Due to its physical properties, grey cast iron has wide applications in different industries' apparatus. Necessary properties can be transmitted in grey cast iron through methods of processing such as annealing, etc. Different methods of processing are performed to impart the necessary matrix/stage inside the sample. Various matrices have various physical properties. The existence of these stages is assured through microstructures, which are detected using a metallurgical optical microscope [13]. Austempered and toughened grey cast iron has improved physical properties compared to grey cast iron [14]. Because of its extensive range of uses, the evaluation of ADI (Austempered Ductile Iron) gains significance. Fractographic investigation is also one of the techniques for material classification [15]. Tempering enhances the quality at the cost of toughness through converting the parent matrix into a completely ferritic structure, while higher toughness can be achieved by immersing the sample into a salt bath (austempering) from the austenitizing temperature. This results in the formation of either an upper or lower bainitic structure, depending on the cooling rate [16, 17]. The mechanical properties of ductile cast iron, such as UTS (Ultimate Tensile Strength) and toughness, improve with an increase in pearlite content, while a ferritic matrix results in increased ductility and impact strength [18].

The primary objective of this paper is to present a comprehensive overview encompassing the microstructural attributes, mechanical properties, processing methodologies, and industrial applications of grey cast iron. By exploring the foundational aspects governing its behavior and performance, an enhanced understanding of this adaptable material can be attained. This, in turn, facilitates progress in its applications, contributing significantly to the broader scope of materials, science and engineering.

MATERIALS & METHODS

Material

The material used in the present research work is Grey Cast Iron of grade FG350.

Methods

Grey cast iron, a type of iron belonging to the cast iron family, is characterized by the presence of flake graphite. It exhibits specific attributes such as strength, hardness, modulus of elasticity, shock absorption, wear resistance, and thermal conductivity. Notably, it excels in casting performance, cutting capabilities, and has a cost-effective casting process. The utility of grey cast iron primarily lies within industries, capitalizing on its robustness and malleable qualities.

The iron's microstructural inclusion of flake graphite is the fundamental factor underpinning its distinctive properties. Cracking is a common occurrence across industries, spanning various fields and research endeavors. Currently, understanding crack behavior is imperative for enhancing product life cycles. Contemporary investigations focus on scrutinizing the crack characteristics of grey cast iron through diverse heat treatment methodologies.

The ongoing investigation forms the core of an extensive endeavor, delving deeply into the intricate mechanical properties and fracture behavior that manifest within ductile iron when subjected to a diverse array of heat treatment protocols. This comprehensive study encompasses a thorough preparatory process, meticulously adhering to the exacting standards stipulated by ASTM E8 and ASTM D256 for the creation of both tensile and impact specimens.

The procedural framework begins with a highly meticulous initial phase of austenitization, precisely conducted at a controlled temperature of 1000°C. This inaugural step is followed by a dynamic and diverse array of cooling and quenching rates, orchestrated with precision to induce highly specific material responses Figure 1.

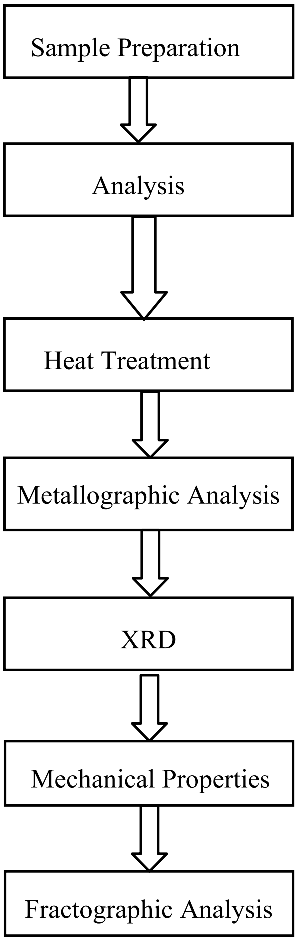

Figure 1. Flow chart of methodology.

The inherent complexity of this multifaceted inquiry is further enriched through a comprehensive exploration into the profound and far-reaching ramifications triggered by tempering, normalizing, and austempering processes. Each of these distinctive procedures adheres to a consistent austenitization duration of 90 minutes, while the chosen quenching mediums – including mineral oil, air, and a specialized salt bath – are meticulously tailored to synchronize seamlessly with the distinct demands intrinsic to each unique process.

In pursuit of a holistic and comprehensive understanding of the material's intrinsic properties and ensuing responses, a meticulously planned regimen of isothermal annealing is astutely employed, selectively applied to a thoughtfully curated subset of specimens. This strategically designed approach permits a meticulous and exhaustive comparative evaluation, shedding light on the material's multifarious responses under varying conditions.

Within the realm of mechanical evaluation, the meticulous execution of tensile testing is orchestrated through the strategic utilization of the INSTRON-1195 apparatus. Similarly, the evaluation of Izod Impact entails a similar level of precision, achieved through the dedicated employment of an Izod impact tester. Furthermore, the quantification of Vickers hardness is pursued with methodical rigor, entailing the precise application of a 20 kg load, sustained for a controlled duration of 10 seconds, facilitated with the invaluable aid of the specialized Vickers Hardness Tester.

Following this comprehensive battery of meticulously conducted mechanical assessments, the study takes a profound and exhaustive turn, with an intense focus on the intricate scrutiny of fracture surfaces exhibited by both heat-treated and as-cast specimens. This nuanced and detailed task is executed with judicious care, facilitated by the discerning application of a Scanning Electron Microscope (SEM).

The culmination of this rigorously conducted and exacting study yields a readily discernible and noteworthy pattern, encapsulating the mechanical attributes exhibited by the specimens under scrutiny. Notably, a zenith of tensile strength is achieved within the tempered and hardened specimens, a striking contrast to the annealed counterparts, which conspicuously display an augmentation in ductility.

However, this heightened ductility is not without its attendant trade-offs, as it necessitates a concurrent reduction in strength. An intriguing and revealing distinction emerge as the annealed specimens distinctly exhibit a fundamentally ductile nature, which stands in stark contrast to the more intricate and multifaceted mode of failure that becomes evident within the tempered, hardened, and normalized counterparts.

RESULTS – METALLOGRAPHIC ANALYSIS

The quantitative metallographic investigation was conducted on each of the treated samples and compared to the as-cast sample. The results are shown in Figure 2.

As per analysis, graph of annealed surface has greater grain size as compared to other heat treatment processes that make the material soft and easily machined. As-cast treatment has low grain size so that it behaves harder material (Figure 2).

HEAT TREATMENT ANALYSIS

Hardening and Tempering

The specimen is austenitized at 1000°C for 90 minutes, swiftly cooled in mineral oil at 100°C, held at that temperature for 30 minutes, annealed at 500°C for 120 minutes, and gradually cooled to room temperature (Figure 3).

Normalizing

The samples are austenitized at 1000°C and held for 90 minutes. After austenitization, the samples are air-cooled to room temperature (Figure 4).

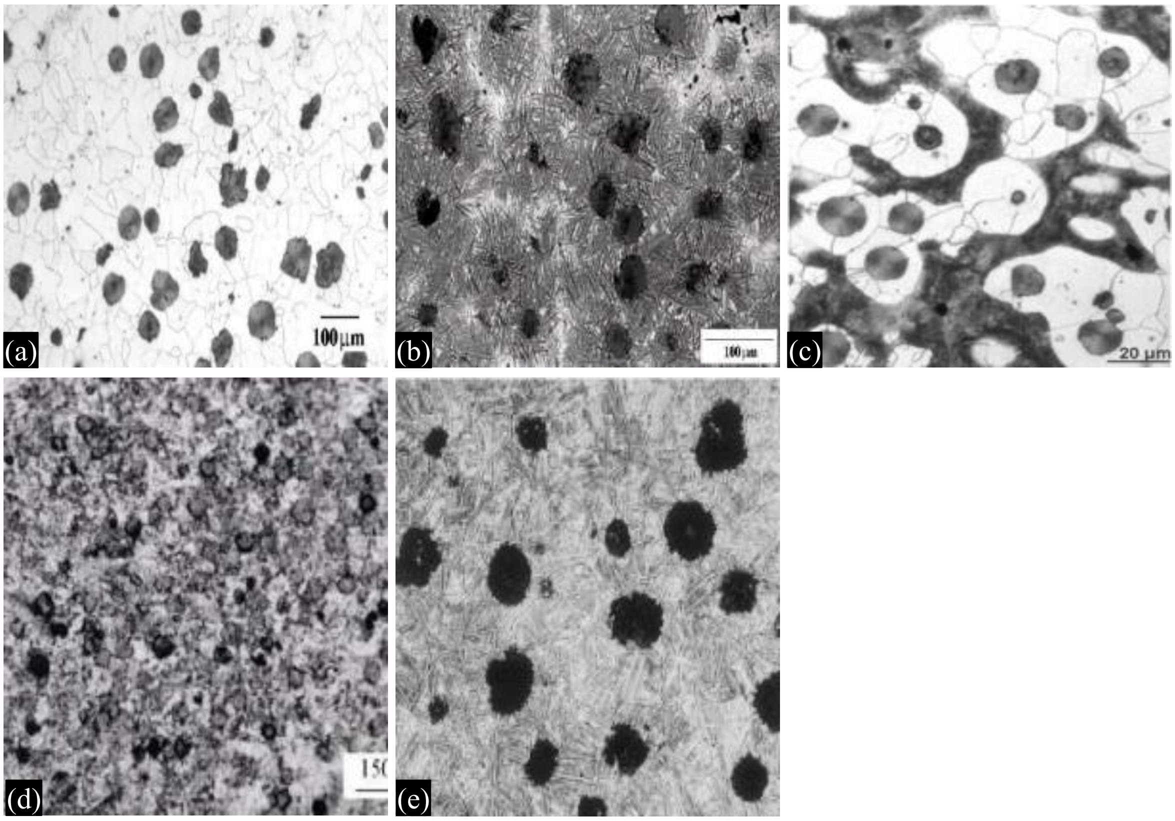

Figure 2. Metallographic analysis of different phases. (a) As-cast, (b) Hardened and tempering, (c) Annealed, (d) Normalized, (e) Austempered.

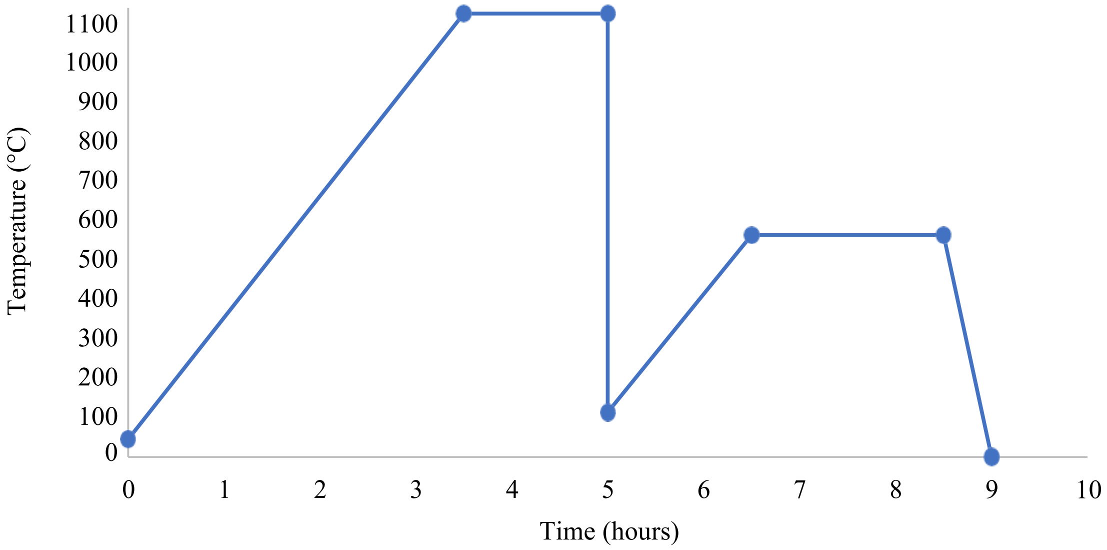

Figure 3. Hardening and tempering process graph.

Annealing

The specimen is subjected to austenitization at 1000°C for 90 minutes, followed by furnace cooling to 700°C and a 5-hour 30-minute hold. Subsequently, the specimen is gradually cooled to room temperature within the furnace (Figure 5).

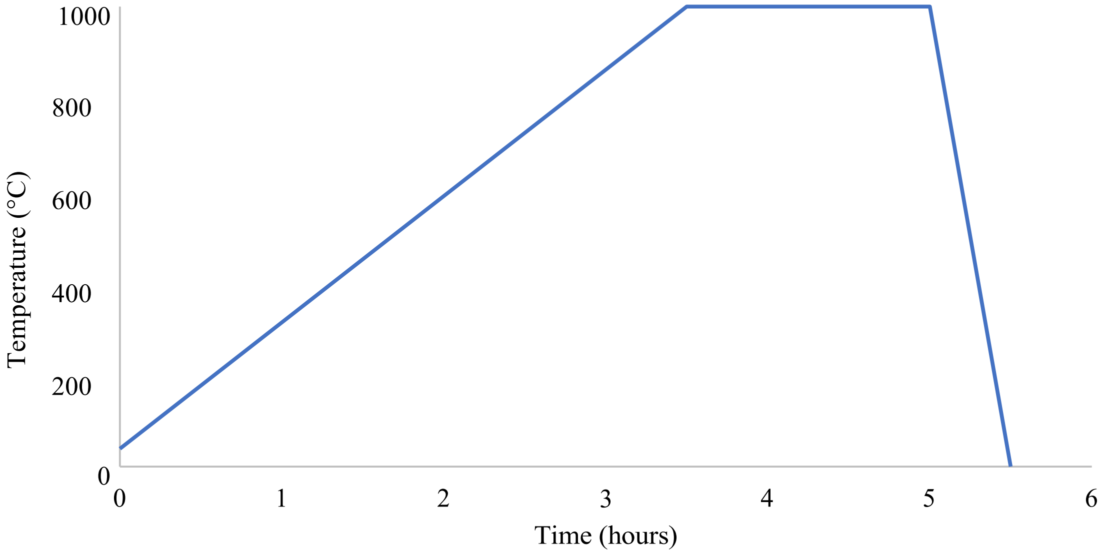

Figure 4. Normalizing process graph.

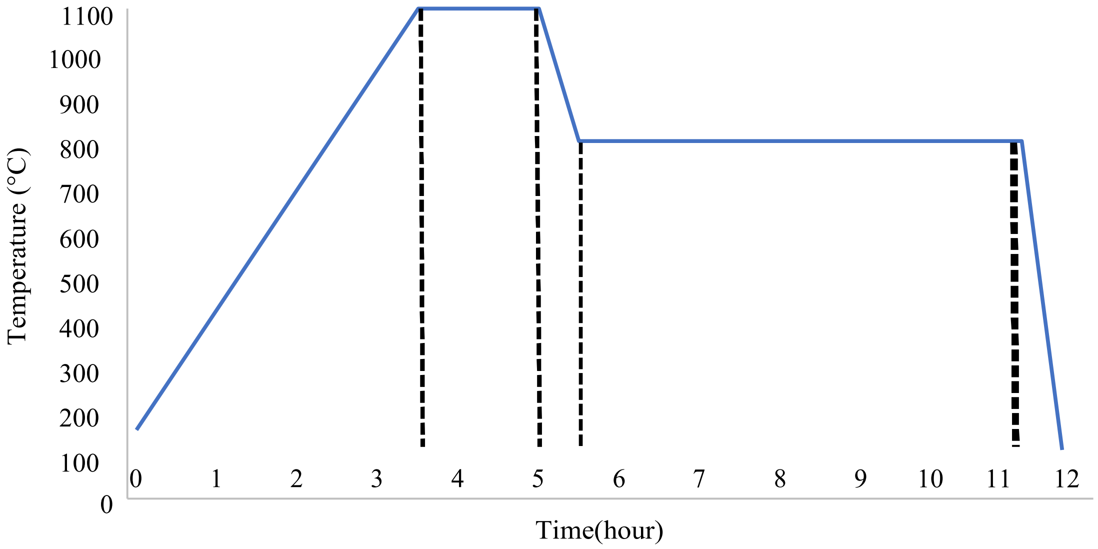

Figure 5. Annealing process graph.

Austempering

Samples undergo austenitization at 1000°C for 90 minutes. Subsequently, they requenched in a 1:1 $NaNO_3$ and KNO_3 salt bath at 500°C for 4 hours, followed by removal and air cooling to room temperature (Figure 6).

XRD ANALYSIS

X-ray Diffraction, commonly referred to as XRD, functions as a robust analytical technique utilized to delve into the intricate architectures of materials at both the atomic and molecular scales [19]. This method finds extensive applicability across a spectrum of scientific fields, spanning disciplines including chemistry, physics, materials science, geology, and engineering.

At its fundamental core, X-ray diffraction operates based on the principle that, as they traverse a crystalline substance, X-rays interact with the regularly ordered atoms positioned within the crystal lattice. This interaction triggers the dispersion of X-rays in various directions. Consequently, the resulting scattered X-rays either harmoniously combine or interfere in a counteractive manner, leading to the creation of a distinct diffraction pattern that can be captured using a detector.

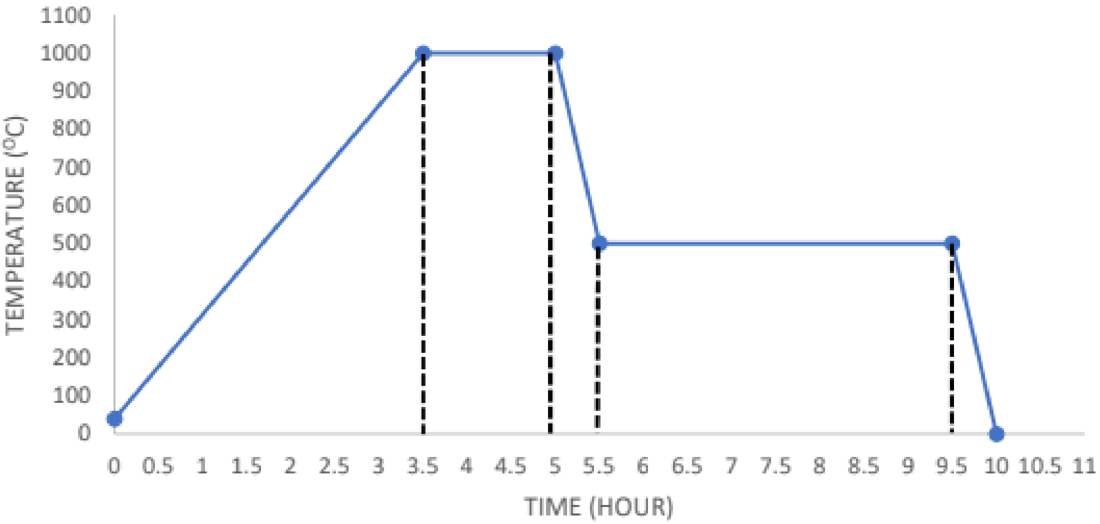

Figure 6. Austempering process graph.

By rigorously scrutinizing this pattern arising from X-ray diffraction, researchers can derive invaluable insights into critical specifics concerning the crystal's lattice spacing, the exact arrangement of atoms within the crystal, and other indispensable structural attributes. This wealth of information plays an essential role in the recognition and exhaustive characterization of crystalline materials, spanning diverse domains such as minerals, metals, ceramics, polymers, and beyond (Figures 7–9 and Table 1).

Table 1. XRD analysis.

Specimen	**Planes**	**Crystal Size (nm)**	**Crystal Structure**	**Residual Strain (%)**
Tempering	(110), (200), (211)	225	BCC	0.342
Annealing	(110), (200), (211)	123	BCC	0.164
Austempering	(110), (200), (211)	97	BCC	0.323
As-cast	(110), (200), (211)	42	BCC	0.205
normalizing	(110), (200), (211)	31	BCC	0.249

MECHANICAL PROPERTIES

The result of all the mechanical properties tested for different heating treatment process are displayed (Figures 10–19 and Table 2).

Table 2. Mechanical properties result.

Specimen	**Tests**				
	Ultimate Tensile Strength	**Yield Strength**	**Elongation**	**Hardness Test**	**Impact Test**
As-Cast	360.21	159.92	31.86	278.02	N/A
Anneal	335.92	160.1	32	219.83	N/A
Normalized	690.86	244.72	12.09	506	8.19
Hardening and Tempering	1156	721.8	13.29	609	10.21
Austemper	841.7	357	13.98	444	9.97

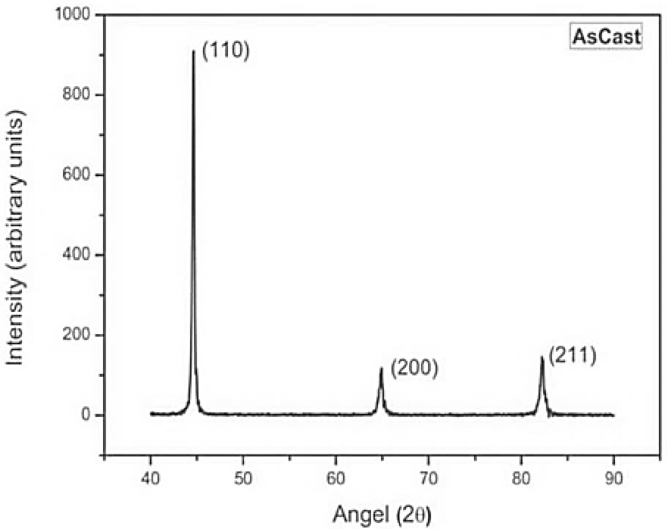

Figure 7. XRD images of as-cast specimens.

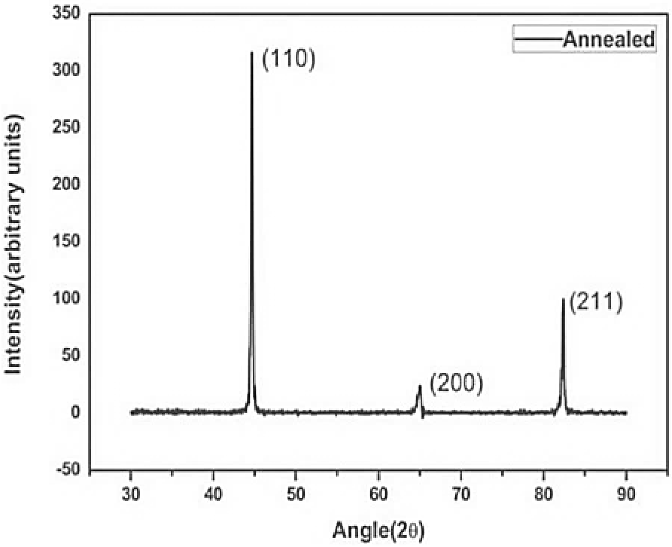

Figure 8. XRD images of annealing specimens.

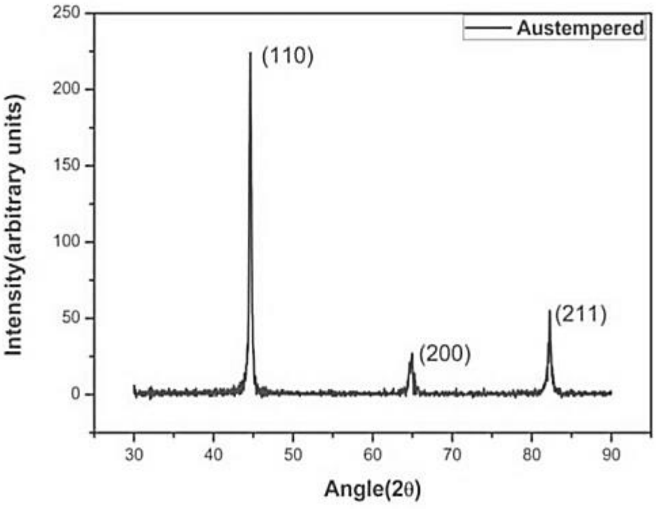

Figure 9. XRD images of austempering specimen.

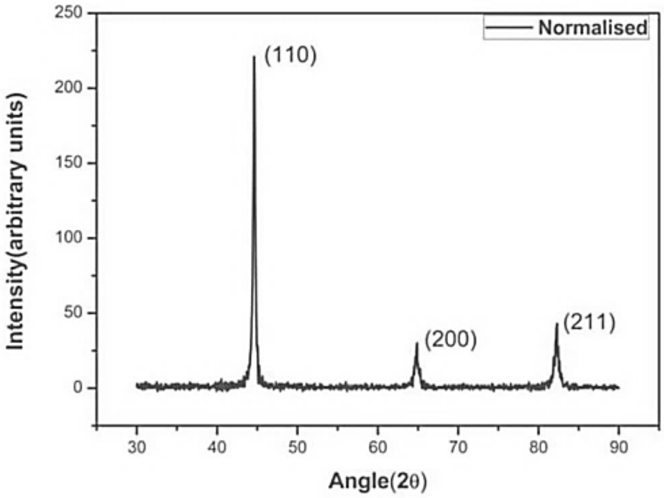

Figure 10. XRD images of normalizing.

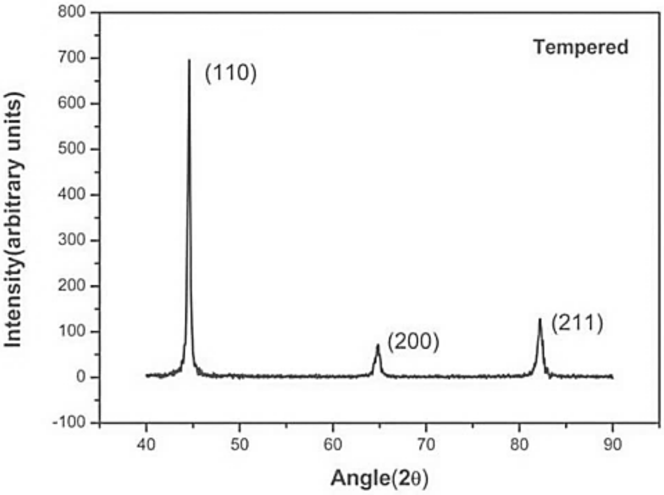

Figure 11. XRD images of hardening & tempering.

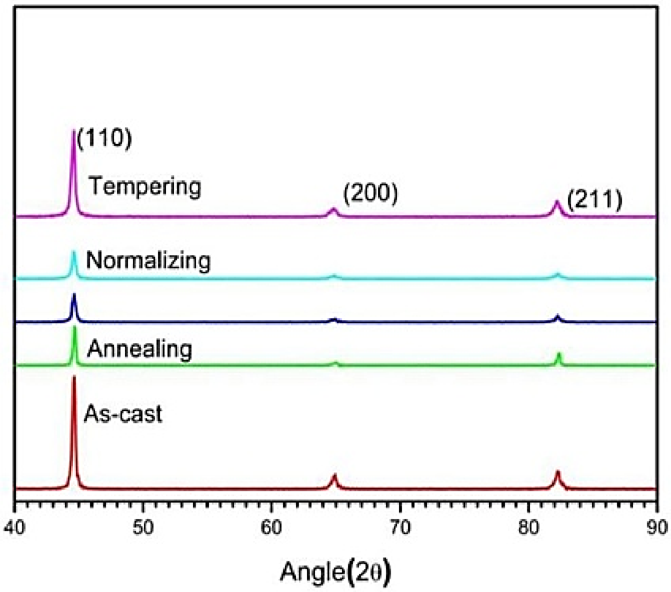

Figure 12. XRD images combined.

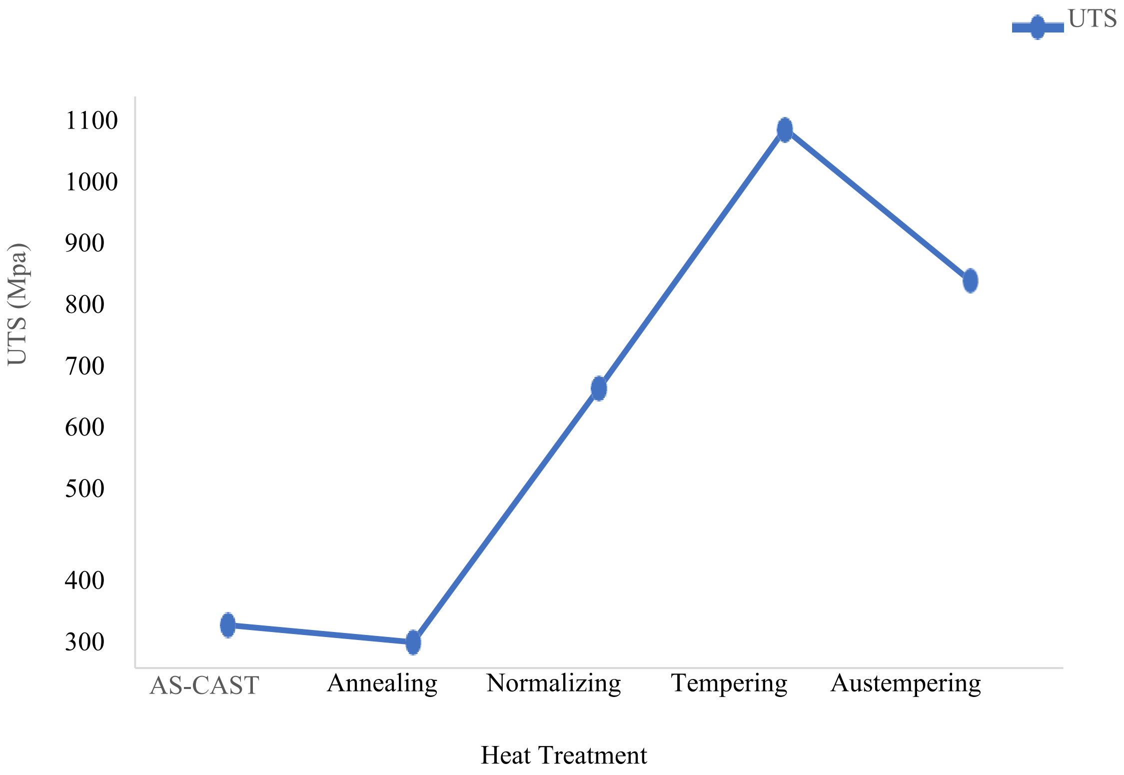

Figure 13. Ultimate tensile strength of as-cast sample and heat-treated specimen.

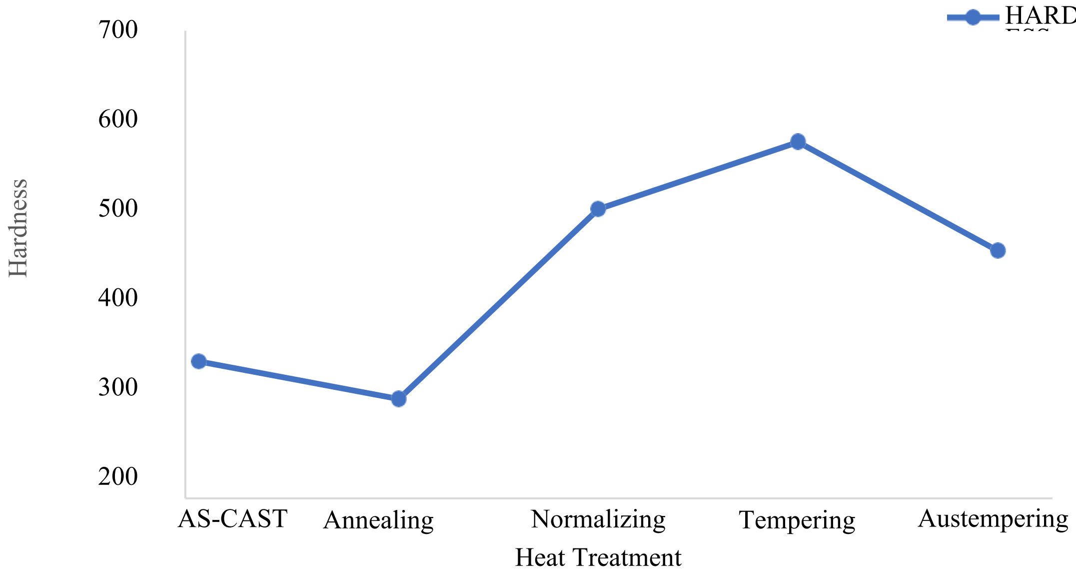

Figure 14. Hardness of as-cast sample and heat-treated specimens.

FRACTOGRAPHIC ANALYSIS

Fracture surface of both the samples, thermal process and as cast samples are detected in the Scanning Electron Microscope at 250X and 500X magnifications and as shown in Figures 20–27.

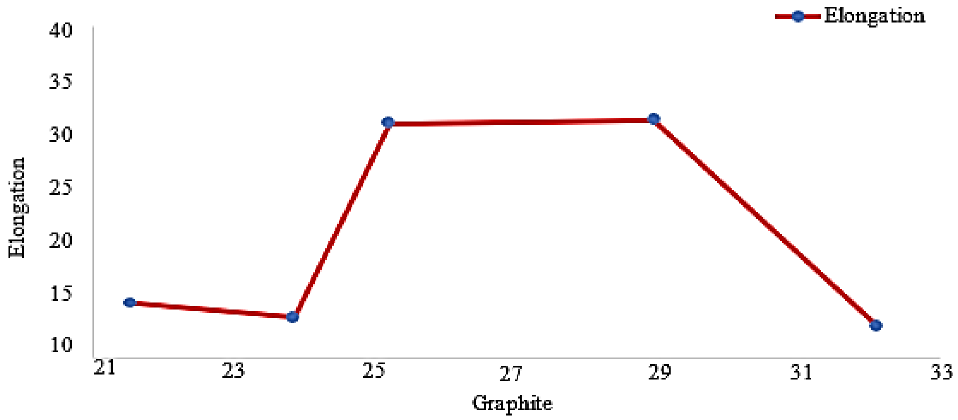

Figure 15. Elongation test versus graphite area fraction (%).

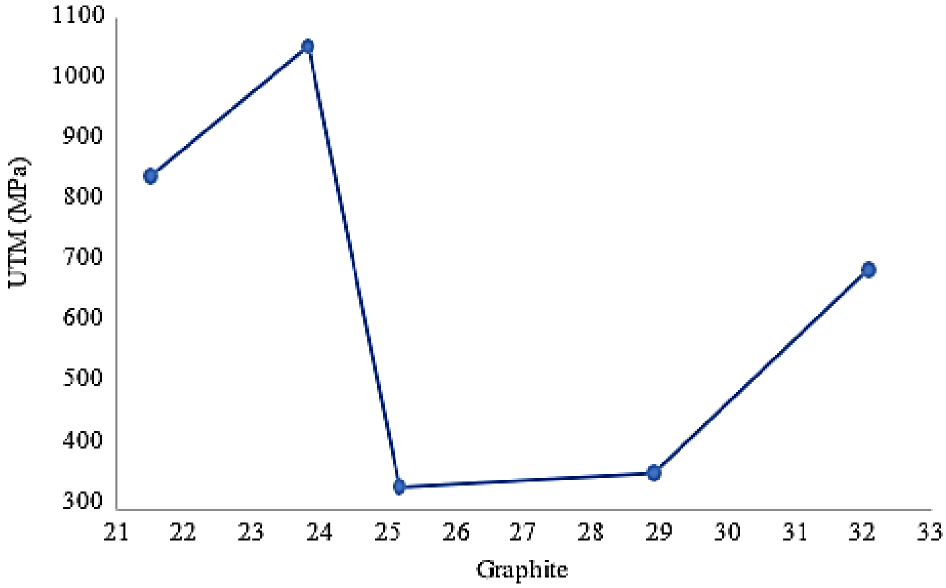

Figure 16. Ultimate tensile strength versus graphite area fraction (%).

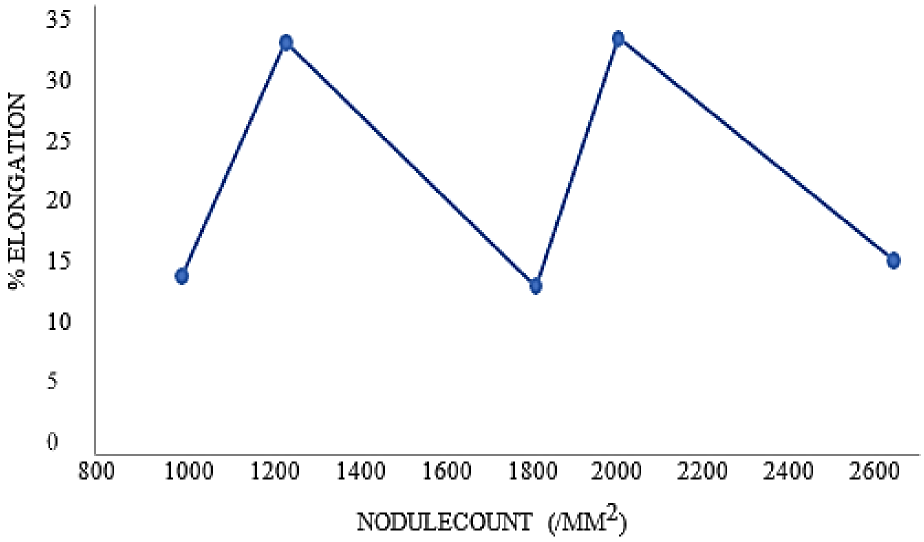

Figure 17. Elongation test versus nodule count.

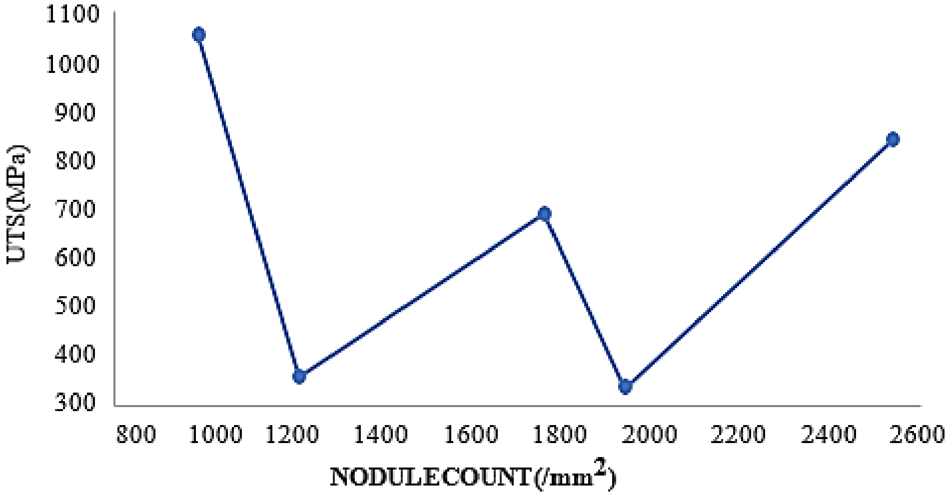

Figure 18. Ultimate tensile strength v/s nodule count.

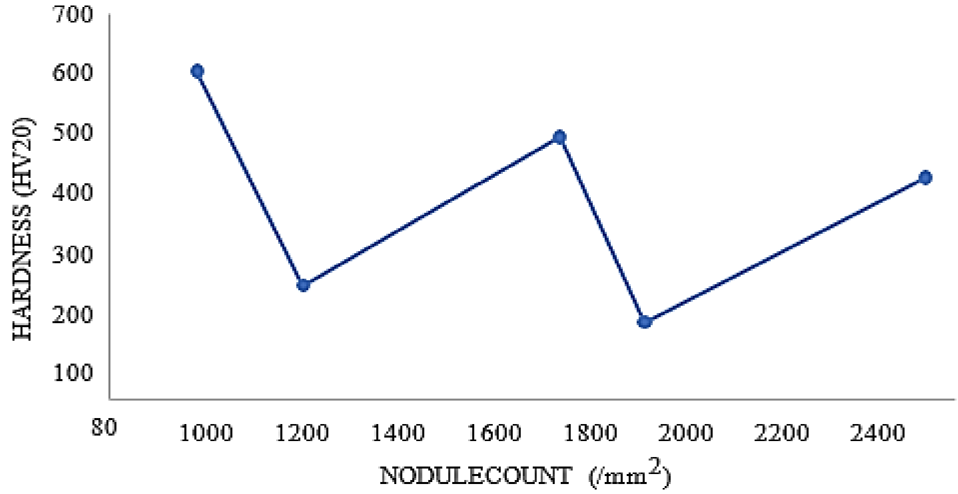

Figure 19. Hardness test v/s nodule count.

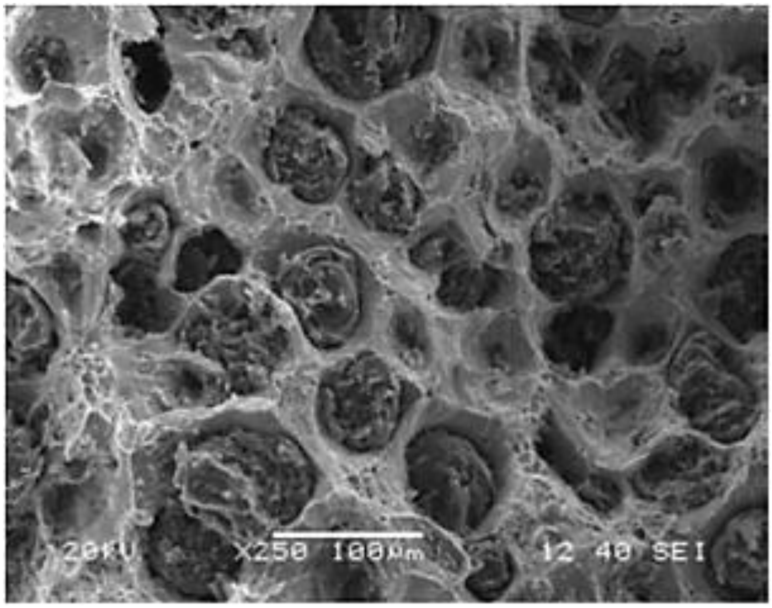

Figure 20. As cast at 250x.

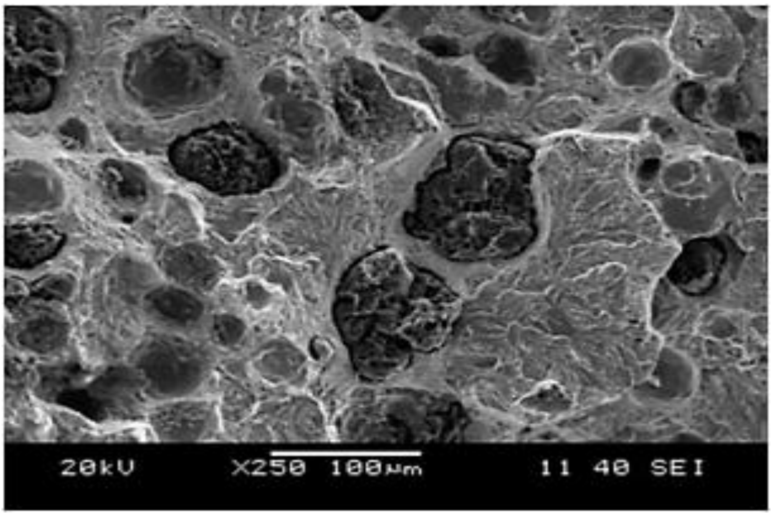

Figure 21. Hardened & tempered at 250x.

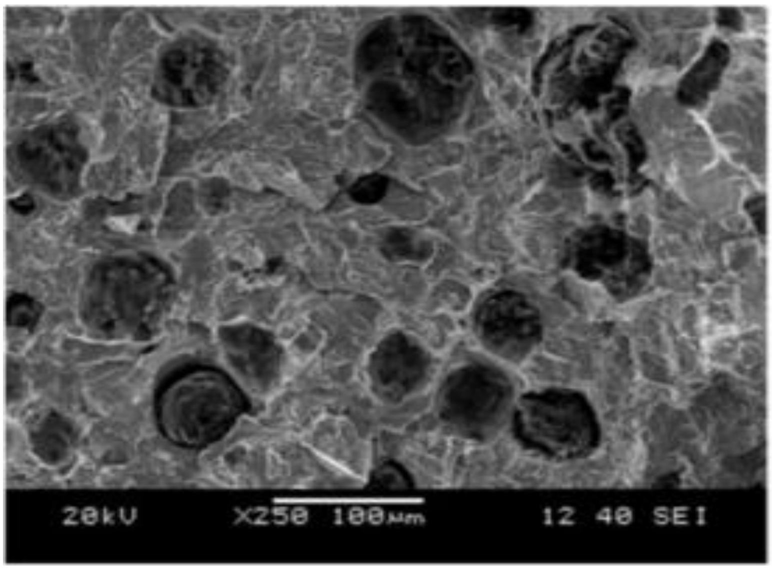

Figure 22. Normalized at 250x.

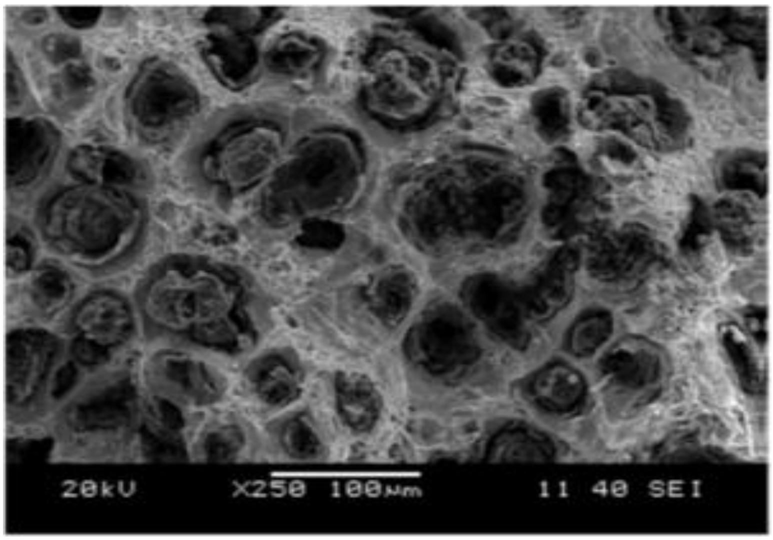

Figure 23. Annealed at 250x.

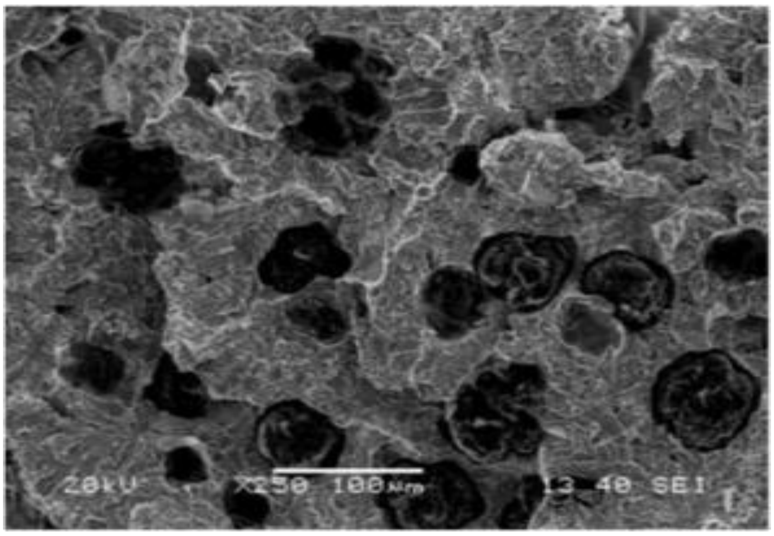

Figure 24. Austempered at 250x.

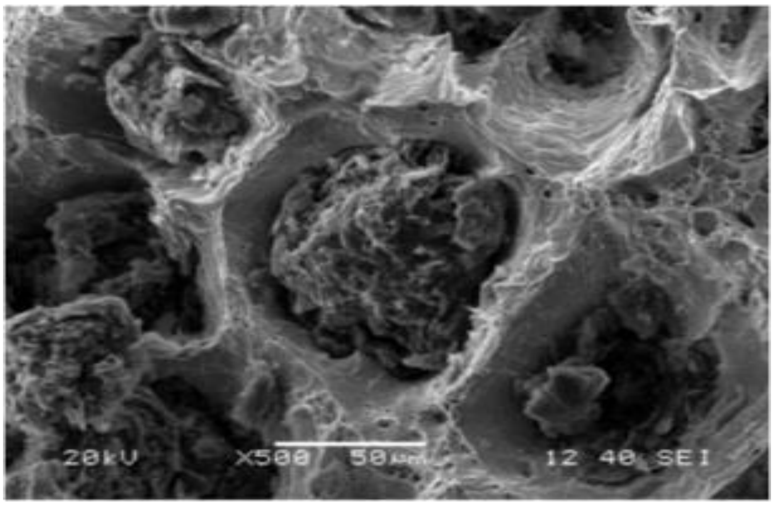

Figure 25. As cast at 500X.

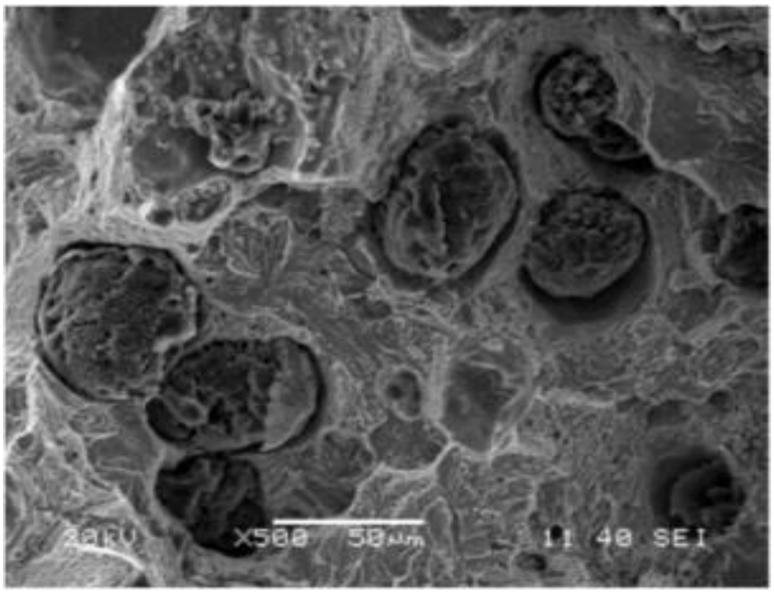

Figure 26. Hardened & tempered at 500X.

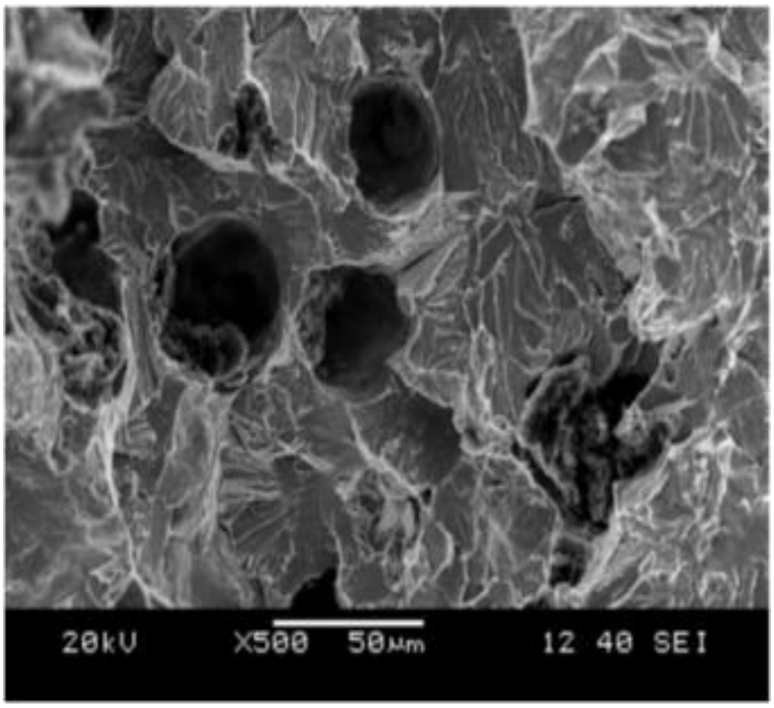

Figure 27. Normalized at 500X.

CONCLUSIONS

Grey cast iron specimens undergo a series of distinct thermal processes, followed by a comprehensive investigation into their physical properties, microstructural attributes, and fractographic characteristics. The most recent analysis unveils the following findings:

The annealing thermal process fosters an elevated level of uniformity within the matrix, resulting in improvements in nodularity, percentage expansion, and impact energy. However, this enhancement is achieved at the expense of both ultimate tensile strength (UTS) and toughness.

Conversely, the toughened and annealed samples showcase the highest UTS and toughest levels, albeit accompanied by a slight reduction in flexibility.

The processes of normalization and austempering yield UTS and toughness values that fall between those of the centrally tempered and toughened & annealed samples. It is noteworthy that normalized samples exhibit diminished flexibility, attributed to the presence of a rigid pearlitic matrix.

X-ray diffraction analysis confirms the existence of a body-centered cubic (BCC) crystal structure in both the as-cast and heat-treated samples.

The modifications in the grey cast iron matrix induced by heat treatment also exert an influence on quantitative metallographic aspects such as nodularity and nodule count.

As-cast and annealed samples, characterized by a complete ferritic matrix, display a distinct ductile fracture pattern marked by the coalescence of microvoids and the occurrence of dimple rupture.

In contrast, the toughened & annealed samples exhibit both river markings and shallow dimples, indicative of a blended mode fracture.

Normalized and austempered samples reveal river markings in contrast to cleavage planes, signifying a brittle fracture mechanism characterized by reduced energy absorption.

REFERENCES

1. Chaengkham P, Srichandr P. Continuously cast ductile iron: Processing, structures, and properties. J Mater Process Technol. 2011;211:1372–8.
2. Gandhi RN. Engineering Properties and Applications of Spheroidal Graphite Iron. In: Proceedings of A Seminar Held in Bombay, 21–22 Feb 1970. Bombay: Institute of Indian Foundrymen; 1971. p. 129.
3. Da S, Zheng YP. A study of the microstructure and properties of continuous casting rare earth ductile iron pipes. J Alloys Compd. 1994;207/208:383–5.
4. Hsu C-H, Lin K-T. A study on microstructure and toughness of copper alloyed and austempered ductile irons. Mater Sci Eng A. 2011;528:5706–12.
5. Rajan TV, Sharma CP, Sharma A. Heat Treatment Principles and Techniques. India: Prentice-Hall India; 2004.
6. Toktas G, Tayanc M, Toktas A. Effect of matrix structure on the impact properties of an alloyed ductile iron. Mater Charact. 2006;57:290–9.
7. Konoplyuk S. Estimation of pearlite fraction in ductile cast irons by eddy current method. NDT & E Int. 2010;43:360–4.
8. Dommarco RC, Sousa ME, Sikora JA. Abrasion resistance of high nodule count ductile iron with different matrix microstructures. Wear. 2004;257:1185–92.
9. Rashidi AM, Moshrefi-Torbati M. Effect of tempering conditions on the mechanical properties of ductile cast iron with dual matrix structure (DMS). Mater Lett. 2000;45:203–7.
10. Karsay SI, Anderson JV. Production of S.G. Iron; 1996.
11. Millis K. Cast Ferrous Alloy. US Patent 2485760; 1949-10-25.
12. Higgins RA. Engineering Metallurgy: Applied Physical Metallurgy. 6th ed. London: Edward Arnold; 1993.
13. Konoplyuk S, Abe T, Uchimoto T, Takagi T, Kurosawa M. Characterization of ductile cast iron by eddy current method. NDT & E Int. 2005;38:623–6.
14. Batra U, Tandon P, Kaur K. A study of austenitization of SG Iron. Bull Mater Sci. 2000;23(5):393–8.
15. ASM Handbook, Formerly 9th Edition, Metal Handbook, Vol. 12, Fractography, Page No. 3.
16. Shaker MA. A note on the effect of nodularization characteristics on the workability of quench-hardened and tempered cast irons. J Mater Process Technol. 1992;32:545–52.
17. Wen DC, Lei TS. Influence of tempering on the mechanical properties of austempered ductile iron. Mater Trans JIM. 1999;40(9):980–8.
18. A Guide to Mechanical Properties of Ductile Iron, Mid-Atlantic Casting Service.
19. Cullity BD. Elements of X-ray Diffraction. Reading, MA: Addison Wesley Publishing Company, Inc.; 1956.