

RESEARCH ARTICLE

Effect of copper addition on solidification behavior, microstructure and hardness of modified low-Ni ductile Ni-resist alloy

M. Aminuddin, M. Mohd Rashidi*

Faculty of Mechanical and Automotive Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, 26600 Pekan, Pahang, Malaysia

Abstract – Because of their excellent thermal properties and stable austenitic matrix, ductile Ni-resist alloys are widely used in corrosion-resistant and high-temperature applications. However, the high nickel content needed to make traditional Ni-resist alloys raises production costs considerably. To assess the impact of Cu substitution on solidification behavior, microstructural evolution, segregation characteristics, and hardness response, modified ductile Ni-resist alloys with a reduced nickel content (18 weight percent Ni) and varying copper additions (6 to 10 weight percent Cu) were prepared. Induction melting, in-mold nodularization, and inoculation were used to create the alloys. X-ray diffraction (XRD), optical microscopy, scanning electron microscopy (SEM–EDS), and dendritic arm spacing analysis were used to characterize the microstructure. The dendritic arm spacing (DAS) increased from roughly 240 μm to 250 μm , and the secondary dendritic arm spacing (SDAS) increased from 20 μm to 24 μm , indicating that increasing Cu content promoted interdendritic segregation and dendritic coarsening. With increasing Cu addition, graphite nodularity gradually dropped from $75.1 \pm 0.3\%$ to $71.3 \pm 0.1\%$, and nodule count dropped from 213.0 ± 1.0 to 201.7 ± 0.6 nodules/ mm^2 . Cu enrichment in interdendritic and grain-boundary regions was confirmed by SEM-EDS analysis, whereas Ni remained comparatively evenly distributed within the γ -austenitic matrix. With a γ -Fe content of roughly 94.61%, XRD analysis confirmed that the FCC austenitic phase was stable in all compositions. Due to solid-solution strengthening and solute segregation, macro-hardness in Cu-rich interdendritic regions increased from 160.0 ± 8.7 HB to 194.3 ± 5.1 HB, while micro-hardness increased from roughly 215.7 ± 7.4 HV to 298.3 ± 1.5 HV. The results show that partial substitution of Cu for Ni can preserve a stable austenitic structure while altering the morphology and hardness behavior of graphite, offering valuable information for the creation of less expensive ductile Ni-resist alloys with regulated microstructural performance.

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1. Introduction

Because of their superior castability, affordable manufacturing costs, favorable wear resistance, and ease of machining, cast irons continue to be one of the most popular engineering materials. Automobile parts, pumps, pipes, machine bases, and thermal systems are only a few of their numerous industrial uses. However, the shape of graphite generated during solidification has a significant impact on the mechanical performance of cast irons. Gray cast iron has comparatively low tensile strength, ductility, and fatigue resistance due to the presence of graphite in the form of linked flakes that serve as stress concentrators. While maintaining the superior casting properties of traditional cast iron, the formation of ductile iron through magnesium treatment converts flake graphite into spheroidal graphite, greatly enhancing strength, toughness, and resistance to crack initiation [1], [2], [4]. Despite these advancements, phase change and oxidation cause microstructural instability in typical ductile iron at high temperatures, which restricts its use in harsh thermal and corrosive conditions. As a result, alloy modification has emerged as a successful strategy for increasing the ductile cast iron's service capacity under challenging operating circumstances [5], [6].

Austenitic ductile Ni-resist alloys have garnered significant interest among the many alloyed cast irons due to their superior mechanical performance across a broad temperature range, thermal stability, dimensional stability, corrosion resistance, and oxidation resistance. These better qualities are attained principally by the inclusion of nickel, which stabilizes the γ -austenitic matrix and suppresses the ferrite change during cooling [6]. To maximize microstructure and service performance, ductile Ni-resist alloys typically contain between 18 and 36 weight percent Ni along with alloying elements like Cr, Mn, and Cu [7], [8]. As a result, ductile Ni-resist alloys have been widely used in applications where superior thermal stability and corrosion resistance are crucial, such as exhaust manifolds, turbocharger housings, heat-resistant pumps, furnace components, marine systems, and chemical processing equipment [7], [9].

Nickel is one of the costliest alloying elements in ductile Ni-resist cast irons, despite offering superior austenite stability and corrosion resistance. Therefore, considerable efforts have been made to develop lower-Ni austenitic ductile irons without compromising microstructural stability and mechanical performance due to the rising cost and variable availability of Ni. Partially replacing Ni with Cu is a viable strategy since Cu also enhances austenite stability and provides solid-solution strengthening at a significantly lower material cost [5], [10]. Cu substitution, however, cannot be viewed just from a compositional perspective. Cu shows partitioning behavior during solidification that encourages enrichment in Late-To-Freeze (LTF) and interdendritic regions, changing the final microstructure, local chemical homogeneity,

dendritic evolution, and graphite nucleation. Therefore, creating low-Ni ductile Ni-resist alloys that are economically appealing requires an understanding of how Cu affects solidification behavior.

Cu has been shown in earlier studies to have a major impact on the microstructural evolution and solidification behavior of ductile cast irons. While preserving the stability of the γ -austenitic matrix, moderate Cu additions strengthen the matrix through solid-solution strengthening. However, increasing the Cu content also encourages microsegregation during solidification, resulting in enrichment in LTF and interdendritic regions where the local chemical composition differs from that of the dendritic cores [11]. Dendritic arm spacing (DAS/SDAS), graphite growth kinetics, carbide formation tendencies, and localized hardness are all impacted by the redistribution of Cu during solidification. Due to alterations in the local solidification path and solute redistribution, excessive Cu addition has also been shown in several experiments to decrease graphite nodularity and encourage graphite degeneration [12]. These results imply that Cu's metallurgical function goes beyond straightforward alloy substitution and should be assessed in conjunction with the solidification mechanisms controlling microstructural development.

Cu-containing ductile irons have been the subject of several investigations, but most of them have focused on mechanical characteristics, corrosion resistance, oxidation behavior, or general microstructural findings [7], [8], [9]. In austenitic ductile irons, more recent studies have also examined phase evolution, carbide morphology, and thermal stability [5], [6]. Nevertheless, in reduced-Ni ductile Ni-resist alloys, only a small number of investigations have consistently linked Cu-induced microsegregation with dendritic development, graphite shape, and hardness. It is also challenging to determine the metallurgical linkages between solidification behavior, interdendritic segregation, graphite formation, and mechanical response because prior studies have frequently assessed these features separately. While Bork et al. [5] emphasized the significance of alloy chemistry in regulating austenitic stability and carbide morphology, recent work by Shin et al. [12] showed that Cu segregation during solidification greatly affects the final microstructure of ductile iron. However, there is still a lack of knowledge on the quantitative relationships among Cu content, dendritic arm spacing, graphite nodularity, and localized hardness in modified low-Ni ductile Ni-resist alloys.

Several significant scientific concerns are still unanswered despite significant advancements in the development of Cu-containing ductile and Ni-resist cast irons. The combined impact of Cu addition on solidification-induced microsegregation, dendritic evolution, graphite morphology, and localized mechanical response has received relatively little attention. At the same time, previous research has mostly concentrated on individual properties like hardness, corrosion resistance, oxidation performance, or phase stability. Specifically, with a stable reduced Ni concentration of 18 weight percent, the formation of interdendritic and Late-To-Freeze (LTF) areas has not been thoroughly studied. Furthermore, there is currently a dearth of thorough knowledge regarding the simultaneous effects of increasing Cu content on dendritic arm spacing (DAS/SDAS), graphite nodularity, nodule count, γ -austenite stability, and macro- and microhardness. Optimizing alloy composition while balancing production cost, microstructural integrity, and mechanical performance requires addressing these interactions.

Establishing a comprehensive understanding of the relationship between Cu addition, solidification-induced microsegregation, dendritic evolution, graphite morphology, phase stability, and hardness response in modified low-Ni ductile Ni-resist alloys with a fixed Ni content of 18 weight percent is what makes this study novel. The current work uses optical microscopy, SEM-EDS, XRD, dendritic arm spacing analysis, and macro- and microhardness measurements to explain the metallurgical mechanisms governing microstructural evolution during solidification, in contrast to earlier studies that mainly concentrated on individual properties. By elucidating how Cu substitution can lower Ni consumption while preserving a stable γ -austenitic matrix and appropriate graphite shape, the results offer useful information for alloy design. This knowledge aids in the creation of more affordable ductile Ni-resist alloys for corrosive and high-temperature industrial uses.

Thus, the purpose of this study is to examine how the microstructural evolution, dendritic structure (DAS/SDAS), microsegregation behavior, graphite morphology, phase stability, and hardness response of modified ductile Ni-resist alloys are affected by increasing the Cu content from 6 to 10 weight percent while keeping the Ni content fixed at 18 weight percent. In order to provide a metallurgical foundation for improving alloy composition in low-Ni ductile Ni-resist systems, the study also attempts to determine the correlations between Cu-induced interdendritic segregation, graphite nodularity, nodule count, and macro- and microhardness.

2. Materials and Methods

2.1 Alloy Preparation and Castings Process

Steel scrap, pig iron, electrolytic nickel, and pure copper were used as the main charge materials in an induction melting furnace to create modified ductile Ni-resist alloys. The target alloy compositions were 6Cu–18Ni, 7Cu–18Ni, 8Cu–18Ni, 9Cu–18Ni, and 10Cu–18Ni, respectively, with a fixed nickel content of 18 weight percent and variable copper additions of 6, 7, 8, 9, and 10 weight percent. This compositional design was intended to assess the effects of progressive Cu substitution on microstructural evolution, segregation properties, and solidification behavior while preserving a stable austenitic matrix.

To guarantee total dissolution and homogenization of the alloying elements, the melting process was conducted in an induction furnace at about 1500 ± 20 °C. To enhance chemical homogeneity and lessen compositional segregation, the molten metal was periodically stirred during the melting process. The molten alloy was superheated before casting in order to enhance fluidity and encourage the dissolution of any remaining inclusions.

A controlled pouring temperature of $1400 \pm 20^\circ\text{C}$ was used to pour the molten alloy into green sand molds. Bentonite, water, and silica sand were used to create the molds. To reduce differences in solidification behavior between compositions, all castings were made under the same molding and cooling conditions. For microstructural and mechanical analysis, cylindrical cast samples measuring roughly 25 mm in diameter and 100 mm in length were made.

To encourage graphite spheroidization, inoculation and in-mold nodularization methods were used. In a specially constructed reaction chamber inside the runner system, a FeSiMg nodularizer containing roughly 5 weight percent Mg with particle sizes ranging from 1 to 4 mm was added at a dosage greater than 1.1 weight percent of the molten metal. In order to improve graphite nucleation and decrease carbide formation during solidification, a FeSi-based inoculant was added concurrently. Table 1 summarizes the chemical compositions of the alloying additions and raw materials.

2.2 Metallographic Preparation

Specimens were separated from the cast samples for metallographic analysis once they had solidified and cooled to room temperature. In order to achieve a mirror-like surface finish appropriate for optical microscopy, scanning electron microscopy (SEM), and hardness testing, the specimens were sequentially ground using SiC abrasive papers ranging from 240 to 2000 grit, and then polished using $0.3\ \mu\text{m}$ alumina suspension.

Selected samples were etched using a 2% nital solution for microstructural observation, revealing the matrix components, graphite morphology, and dendritic structure. Using optical microscopy, graphite morphology, nodularity, and nodule count were assessed in compliance with ASTM A247 and A439 standards. To get representative average values, at least five distinct observation fields were examined for every composition.

2.3 Microstructural Characterization

Scanning electron microscopy (SEM) and optical microscopy were used for microstructural analysis. A field-emission scanning electron microscope with energy dispersive spectroscopy (EDS) for elemental analysis and segregation assessment was used for SEM observations. The SEM analysis was conducted in secondary electron imaging mode with an accelerating voltage of 15–20 kV. Dendritic cores, interdendritic regions, graphite nodules, and Late-To-Freeze (LTF) zones were among the representative regions examined.

To ascertain the distribution of Fe, Ni, Cu, Si, and Mg within the microstructure, elemental mapping and compositional analysis were carried out using SEM–EDS. The identification of Cu segregation behavior in interdendritic and grain boundary regions was given special attention.

2.4 Dendritic Arm Spacing (DAS and SDAS Measurement)

Image analysis software was used to measure the primary dendritic arm spacing (DAS) and secondary dendritic arm spacing (SDAS) from SEM micrographs. The linear intercept method was used to measure well-developed dendritic regions. To guarantee statistical reliability, at least 20 separate measurements were taken from several micrographs for every alloy composition. The average distance between neighboring primary dendritic trunks was used to calculate DAS values, whereas the distance between secondary dendritic arms was used to calculate SDAS values. To assess the impact of Cu addition on dendritic coarsening behavior during solidification, the average values were computed and reported.

2.5 X-ray Diffraction (XRD) Analysis

X-ray diffraction (XRD) analysis with Cu-K α radiation ($\lambda = 1.5406\ \text{\AA}$) was used to identify the phase. With a step size of 0.02° , diffraction patterns were captured over a 2θ scanning range of 20° – 100° . To determine whether γ -austenite and secondary phases were present, the obtained diffraction peaks were indexed and compared with standard diffraction data. To assess the stability of the austenitic matrix with increasing Cu addition, the relative γ -Fe content was calculated from the dominant FCC austenitic diffraction peaks.

2.6 Hardness Measurement

The Brinell hardness method was used to measure macro-hardness in compliance with ASTM E10 guidelines. For every measurement, a standard tungsten carbide ball indenter with the proper test load and dwell time was utilized. Each sample surface had at least five indentations made at various points, and the average hardness value was recorded. To assess localized hardness differences between dendritic and interdendritic regions, micro-hardness testing was also carried out using a Vickers microhardness tester. Measurements were made with a controlled dwell time and a fixed load. To evaluate the impact of Cu segregation on local hardness distribution, multiple indentations were made across dendritic cores, interdendritic regions, and Late-To-Freeze (LTF) zones.

2.7 Solidification and Microstructure Analysis

Analysis of dendritic morphology, segregation traits, graphite nodularity, and Late-To-Freeze (LTF) regions was used to assess solidification behavior. To determine the impact of alloy modification on the microstructural evolution of low-Ni ductile Ni-resist alloys, the relationship between Cu addition, segregation tendency, dendritic coarsening, and graphite degeneration was methodically examined.

Table 1. Chemical composition of iron, alloyed materials, nodularizer, inoculant, and Cu (wt %)

Elements							
C	Si	Mn	P	Mg	Ni	Cu	Fe

Pig iron	2.91	2.27	0.12	0.07	-	0.02	-	Balance
Steel	0.20	0.15	0.60	0.03	-	-	-	Balance
Nickel	-	-	-	-	-	99.00	-	Balance
Nodularizer	-	44.00	-	-	5	-	-	-
Inoculant	-	70.00	-	-	-	-	-	Balance
Copper	-	-	-	-	-	-	99.00	-

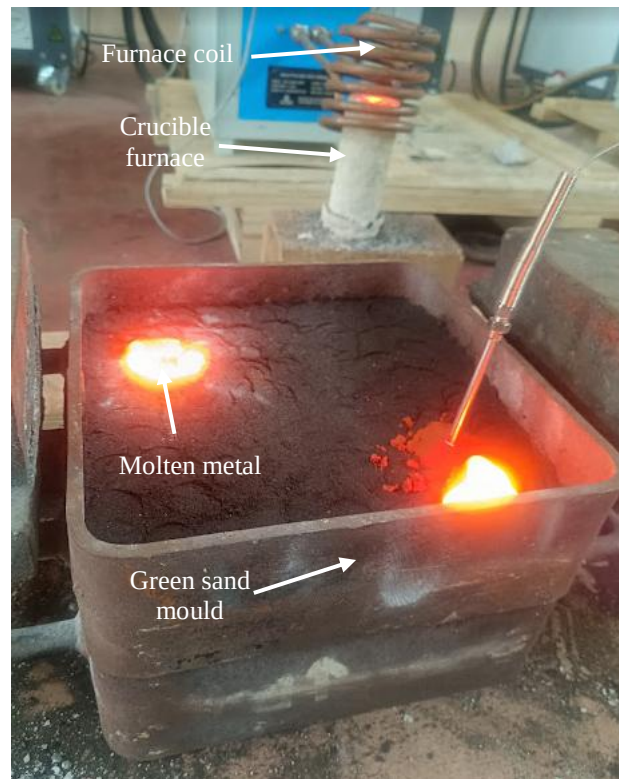


Fig. 1. Setup of molten metal consist of induction furnace, ladle, mould and solidification sample

3. Results And Discussion

3.1 Graphite Morphology and Nodularity

Successful nodularization during casting was indicated by the microstructures of the modified ductile Ni-resist alloys, which showed spheroidal graphite nodules dispersed within a mostly γ -austenitic matrix. Figures 2-4 display representative optical and SEM micrographs. In the lower Cu compositions, the graphite nodules seemed fairly uniform; however, as the Cu content rose from 6 weight percent to 10 weight percent, graphite spheroidization gradually deteriorated.

Graphite nodularity gradually dropped from $75.1 \pm 0.3\%$ for the 6Cu–18Ni alloy to $71.3 \pm 0.1\%$ for the 10Cu–18Ni alloy, according to the quantitative results compiled in Table 3. In a similar vein, as Cu addition increased, the graphite nodule count dropped from 213.0 ± 1.0 to 201.7 ± 0.6 nodules/mm². The results show that higher Cu content slightly inhibited graphite spheroidization and encouraged less uniform graphite growth, despite the moderate reduction.

Nodules of graphite were found in the casting sample (Figure 4). The fact that these graphite nodules form as distinct structures inside the sample suggests that graphite was produced during the solidification or casting process. These nodules contribute to the overall microstructure of the material and might differ in size, shape, and distribution. The graphite nodules are most likely the result of the carbon in the molten metal separating and crystallizing into graphite structures during the solidification process [10]. A semi-spheroidal form, on the other hand, suggests that some of these graphite nodules are incomplete growths. This suggests that either the growth of these graphite structures was stopped during solidification or that the graphite development process may not have been finished.

A hypoeutectic composition with multiple component alloys containing Fe, C, Si, Cu, Ni, and other elements is revealed by the polished surface of the alloy formed during the casting process (Fig. 2), as indicated in Table 2. Austenite matrix, eutectic austenite, graphite aggregate, carbides, and impurity inclusion are the several phases that make up this alloyed iron. Generally, the outer portion of the alloyed iron grain, such as the Last to Freeze (LTF) area, is abundant with positive segregation elements like Mn, whereas the core portion is rich in Ni and Si [8].

Phase formation, element solubility, and solute segregation were among the interrelated metallurgical processes that took place during solidification; in the ductile Ni-resist alloy, nickel and copper showed noticeably different partitioning behaviours. The austenitic phase was stabilized during solidification because nickel, which has a partition coefficient near unity in austenitic iron, preferentially stayed dissolved within the γ -austenite matrix (Table 2). Phase formation, element

solubility, and solute segregation all had a significant impact on the final microstructure and related mechanical behaviour of the modified ductile Ni-resist alloy during solidification. The stability of the austenitic matrix was preserved by the deliberate reduction of the nickel content to at least 10 weight percent, while the gradual addition of copper up to 10 weight percent brought about notable alterations in the microstructural evolution and solidification dynamics.

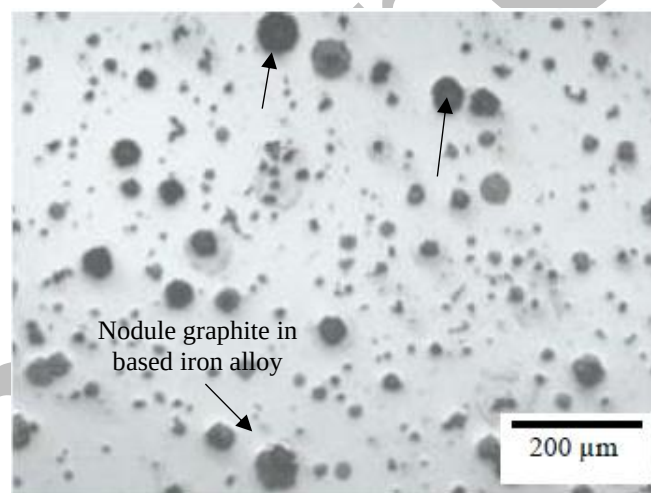
The γ -Fe content, Late To Freeze (LTF), nodularity, and nodule count of the 6Cu–18Ni to 10Cu–18Ni ductile iron castings are summarized in Table 3 and 4. The as-cast structures were confirmed to be a combination of austenite and multiple additional constituents by the X-ray diffraction investigation. The γ -Fe fraction is nearly constant at $94.61 \pm 0.1\%$ across all compositions, suggesting a stable austenitic matrix. This finding is in line with earlier research showing that, despite slight alloying changes, a high Ni content stabilizes the austenitic phase and preserves the matrix composition [13].

All alloys maintained a balanced LTF parameter, indicating that increasing Cu content has little effect on the relative proportion of secondary constituents. This is consistent with research in the literature showing that Cu addition mainly affects graphite morphology rather than dramatically changing the austenite-to-secondary-phase ratio [9].

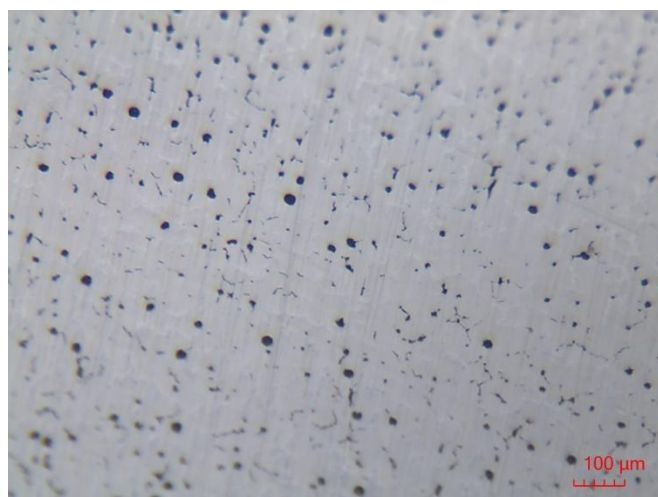
Cu-induced segregation during solidification may be the cause of the noted decrease in nodularity. Carbon diffusion and graphite growth kinetics were locally altered as Cu concentration rose due to preferential solute enrichment in interdendritic and Late-To-Freeze (LTF) regions. The efficiency of Mg-assisted graphite spheroidization may be diminished by excessive Cu accumulation close to grain boundaries, resulting in partially degenerated or semi-spheroidal graphite structures.

All alloys retained nodularity values above 70%, which is generally regarded as acceptable for maintaining the mechanical advantages of ductile austenitic cast iron, despite the nodularity gradually decreasing. This implies that the reduced Ni system with up to 10 weight percent Cu was still able to maintain a stable austenitic matrix and primarily spheroidal graphite morphology.

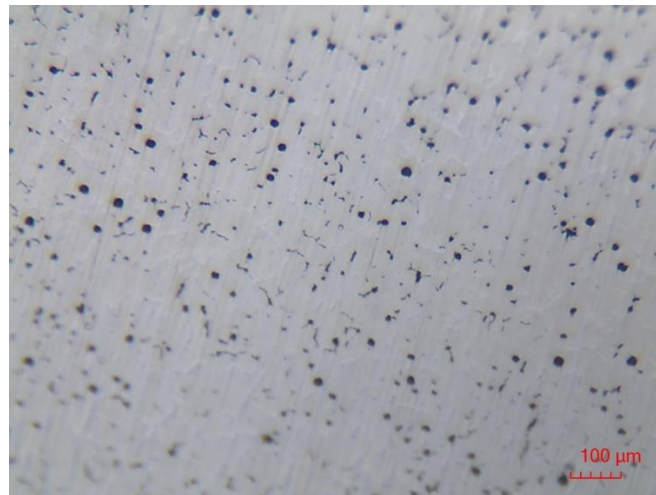
Similar findings have been documented in earlier research on Cu-containing ductile irons, where segregation-induced solidification heterogeneity led to decreased nodule density and increased graphite degeneration as Cu content increased [14]. The current study, however, also shows that this behavior is largely controlled even at lower Ni content, suggesting that partial Ni substitution by Cu in ductile Ni-resist alloys may be feasible.



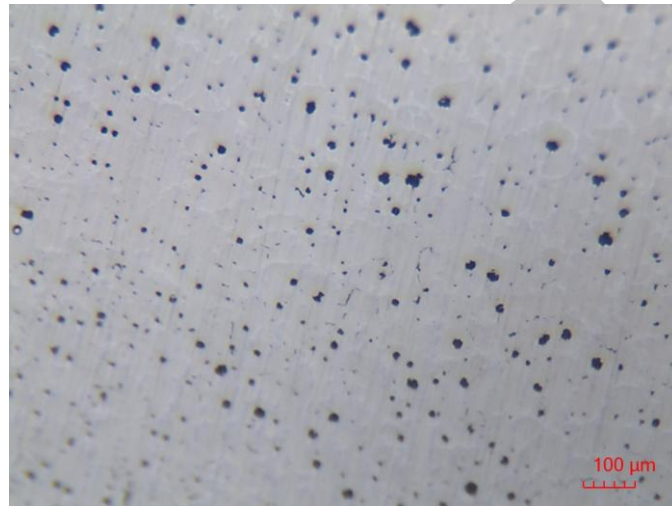
(a)



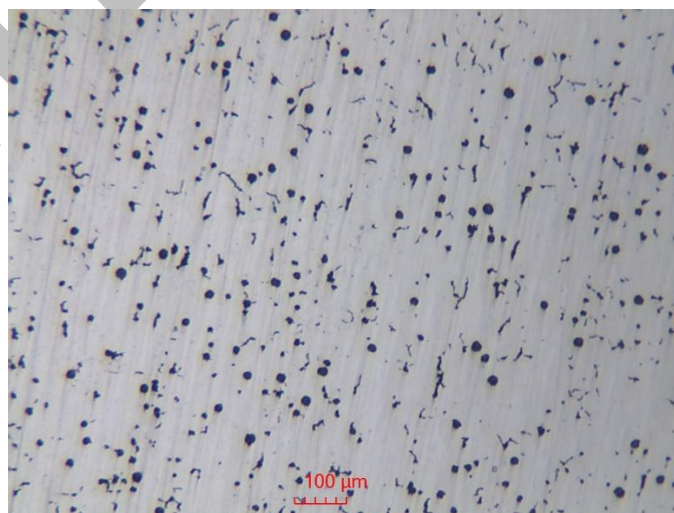
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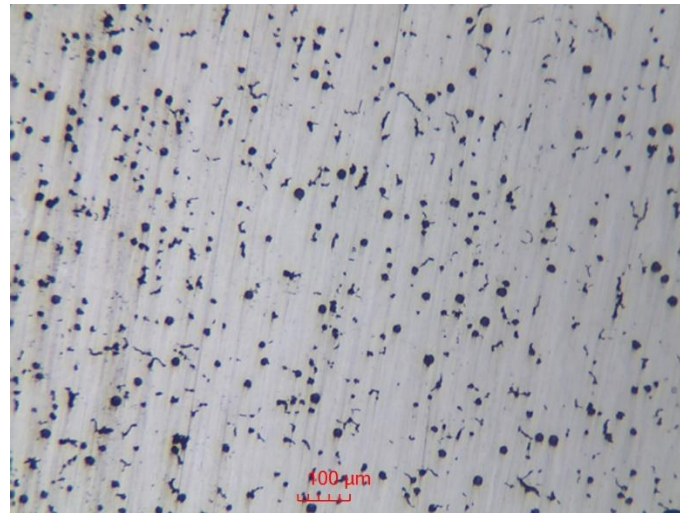
(c)



(d)



(e)



(f)

Fig. 2 (a) Micrograph shows distribution of graphite (arrow) in based alloy, (b) 10Cu-18Ni, (c) 9Cu-18Ni, (d) 8Cu-18Ni, (e) 7Cu-18Ni, and (f) 6Cu-18Ni

Table 2. Compositional analysis of the matrix and interdendritic regions in a ductile Ni-resist alloy with Cu additions using representative SEM-EDS.

Region	Ni (wt.%)	Cu (wt.%)	Fe + Others (wt.%)	Microstructural Implication
Austenitic matrix	~9–11	~2–4	Balance	Stable γ -austenite, uniform phase
Interdendritic/ outer region	~7–9	~8–12	Balance	Cu-rich segregation, graphite degeneration
Grain boundary vicinity	~8–10	~6–10	Balance	Local solute enrichment, stress concentration

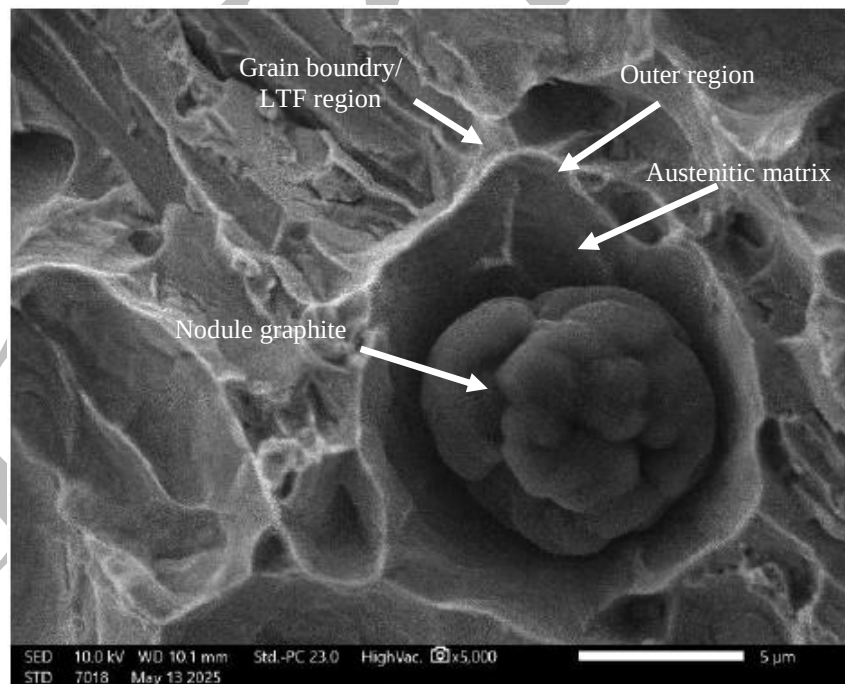


Fig. 3. Micrograph of SEM revealing grain boundary of fractured surface

Table 3. Sample of chemical composition of alloy iron composition (wt %) based on spectrometer

	Elements							
	C	Si	Mn	Cr	Mg	Ni	Cu	Fe
Pig iron	3.30	2.27	0.14	0.45	0.015	17.10	>2.50	Balance

Table 4 Amounts of constituent in the microstructure and its properties

Materials	Y-Fe	Late To Freeze LTF	Nodularity	Nodule count (No./mm ²)
6Cu-18Ni	94.61 $\pm$ 0.1	Balance	75.1 $\pm$ 0.3	213.0 $\pm$ 1.0
7Cu-18Ni	94.61 $\pm$ 0.1	Balance	73.1 $\pm$ 0.1	211.3 $\pm$ 0.6
8Cu-18Ni	94.61 $\pm$ 0.1	Balance	72.4 $\pm$ 0.2	207.7 $\pm$ 0.6
9Cu-18Ni	94.61 $\pm$ 0.1	Balance	71.7 $\pm$ 0.3	204.0 $\pm$ 1.0
10Cu-18Ni	94.61 $\pm$ 0.1	Balance	71.3 $\pm$ 0.1	201.7 $\pm$ 0.6

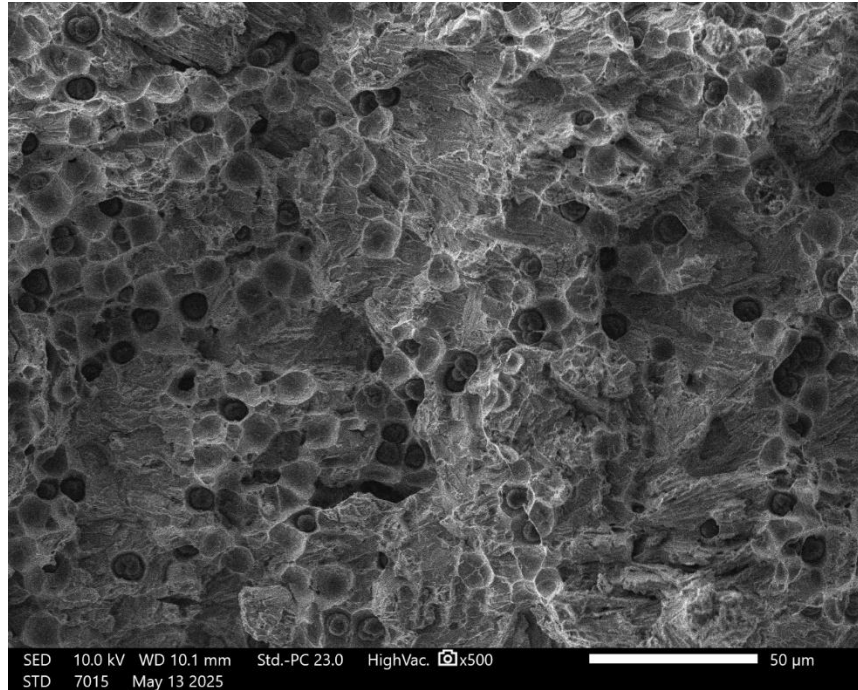


Fig. 4. Micrograph of SEM showing nodule graphite and its shell distributed in macro area of fractured surface

3.2 Dendritic Structure and Solidification Behavior

All alloy compositions showed a well-developed austenitic dendritic structure, according to SEM observations. Figures 5(a) and 5(b) display representative micrographs of primary dendritic arm spacing (DAS) and secondary dendritic arm spacing (SDAS). As is typical of non-equilibrium solidification in highly alloyed cast irons, the dendritic morphology included coarse primary dendritic trunks accompanied by secondary and tertiary dendritic arms. The quantitative measurements demonstrated that progressive dendritic coarsening was encouraged by increasing Cu addition. As shown in Figure 6, the SDAS increased from 20 μ m to 24 μ m while the DAS increased from roughly 240 μ m in the 6Cu–18Ni alloy to roughly 250 μ m in the 10Cu–18Ni alloy. A larger solidification range and slower interface advancement during solidification are indicated by the increase in dendritic arm spacing.

This behavior is mainly related to Cu's partitioning properties during solidification. Cu is rejected into the residual liquid during dendritic growth due to its partition coefficient being less than unity, which results in interdendritic solute enrichment and constitutional supercooling. As a result, the liquidus temperature drops locally, lowering thermal gradients and encouraging dendritic arm coarsening via Ostwald ripening processes. By prolonging the austenite phase field and preventing ferrite formation during cooling, nickel also made a substantial contribution to the stabilization of the γ -austenitic phase. As a result, the combined Ni–Cu alloying system increased dendritic coarsening at higher Cu concentrations while producing a stable austenitic dendritic network.

The current study's coarsening behavior is in line with earlier findings on Cu-containing ductile irons, where higher Cu addition led to coarser dendritic structures and broader freezing ranges under comparable cooling conditions [3]. However, the comparatively mild rise in DAS and SDAS indicates that the alloy maintained metallurgical stability in spite of increasing Cu enrichment.

Late-To-Freeze (LTF) zone formation was also impacted by the growth of coarse dendritic regions. During the last stages of solidification, these interdendritic areas became more and more enriched with Cu, Ni, Mn, and residual solute elements. Because LTF regions are frequently linked to carbide formation, localized hardness increases, decreased graphite nodularity, and stress concentration sites, such segregation behavior is metallurgically significant.

Dendritic solidification behavior is the direct source of LTF regions. Alloying elements (Ni, Cu, and Mn) with partition coefficients less than unity are rejected into the residual liquid as dendrites expand. As a result, the interdendritic liquid solidifies last and becomes more solute-rich. Because these LTF regions are frequently linked to elements like microsegregation, carbide precipitation, shrinkage porosity, and decreased nodularity, they are metallurgically significant.

Research verifies that interdendritic enrichment and deteriorated local mechanical properties are strongly correlated with LTF zones in Ni-Resist alloys. Higher Ni contents (>18 weight percent) may be able to reduce LTF effects because

of improved austenite stability. Nevertheless, segregation-induced defects are not completely eliminated by this mitigation, which is composition-sensitive.

During the last stages of solidification, carbon concentration peaks in interdendritic regions, where graphite nodules preferentially nucleate. Graphite spheroidization requires a dendritic framework, but too much dendritic coarsening can be harmful. A number of factors can be emphasized, including high nodularity and fine, uniform dendrites leading to uniform distribution of graphite nodules. On the other hand, graphite degeneration, decreased nodule count, and nodule clustering are caused by coarse, irregular dendrites. This idea explains why, according to experimental ductile Ni-resist alloys studies, increases in LTF fraction are often accompanied by decreases in nodularity and nodule count.

Research shows that dendritic refinement enhances the stability of graphite morphology in ductile irons, such as ductile Ni-resist alloys systems [4].

Cu is rejected into the liquid during dendritic growth because its partition coefficient, k , is less than 1. This results in slower interface advancement, a decreased local thermal gradient, and solute enrichment in interdendritic liquid. Consequently, arms thicken and coarsen, increasing dendritic size, while dendritic tips grow more slowly. Cu additions also lower the interfacial energy between liquid iron and γ -Fe. Dendritic arms eventually thicken and round out. The arm breakup is then suppressed. Dendritic morphology became smoother and coarser as a result.

A highly developed austenitic dendritic network, a distinguishing microstructural characteristic of ductile Ni-Resist alloys, is visible in the SEM micrograph. The dendrites form a continuous solidification skeleton with irregular primary trunks and well-developed secondary and tertiary arms. This morphology is indicative of solidification under non-equilibrium conditions, where high concentrations of nickel and copper cause constitutional supercooling.

It is hypothesized that nickel extends the austenitic phase field and inhibits the formation of ferrite and pearlite during cooling by acting as a potent γ -Fe stabilizer. Consequently, γ -Fe dominates dendritic growth, and the extended solidification range of Ni-Resist alloys promotes dendritic arm thickening. By decreasing the liquidus temperature and boosting solute partitioning into the liquid phase, copper further intensifies dendritic coarsening.

Higher Ni and Cu contents result in coarser dendritic structures because they shorten thermal gradients and lengthen solute diffusion times. Effective inoculation or quick cooling can prevent excessive dendritic coarsening. This implies that compositional effects may be partially overridden by processing conditions.

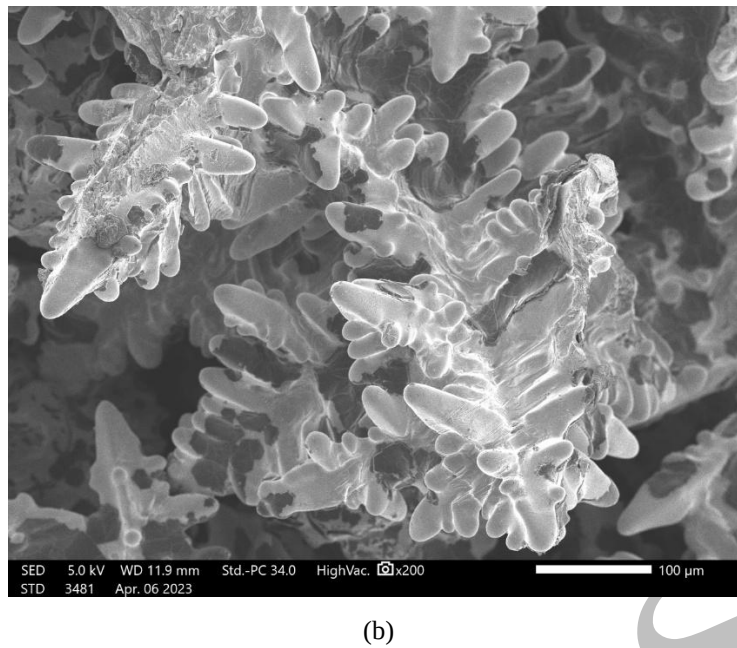
Ni enrichment promotes low solid-liquid interfacial energy, which is indicated by the rounded dendritic arm tips. The estimated dendritic arm spacing (DAS) of several tens of micrometers is in line with the moderate cooling rates that are typical of investment casting or sand. A chemically diverse microstructure is created by the dendrites, where:

Ni, Cu, Mn, and residual elements are enriched in interdendritic regions, while dendritic cores are comparatively lean in solute. Additionally, it is thought that this spatial distribution is essential to comprehending how Late-To-Freeze (LTF) regions form.

In ductile Ni-Resist alloys, Cu typically coarsens dendrites by increasing their size, particularly when cooling conditions remain constant [15], [16]. According to the SEM micrograph, as the Cu addition increases, the dendritic DAS gets bigger. When 10Cu-18Ni is used, the dendritic size increases to about 250 μm from 240 μm at 6Cu-18Ni. the same pattern found at dendritic arm spacing SDAS, which ranged from 20 to 24 μm (Figure 6). There are a number of theories about it. Cu is an austenite stabilizer in ductile Ni-resist alloys, comparable to Ni but weaker, due to its impact on the solidification range. Cu causes the freezing range to expand while the liquidus and solidus temperatures decrease. This resulted in a broader solidification range, which permits increased dendritic arm coarsening (Ostwald ripening) and longer dendritic growth times. Larger primary and secondary dendritic arm spacing (DAS) has resulted from this.



(a)



(b)

Fig. 5. Micrograph shows DAS and SDAS revealed by fractured surface of (a) (6Cu-18Ni) and (b) 10Cu-18Ni.

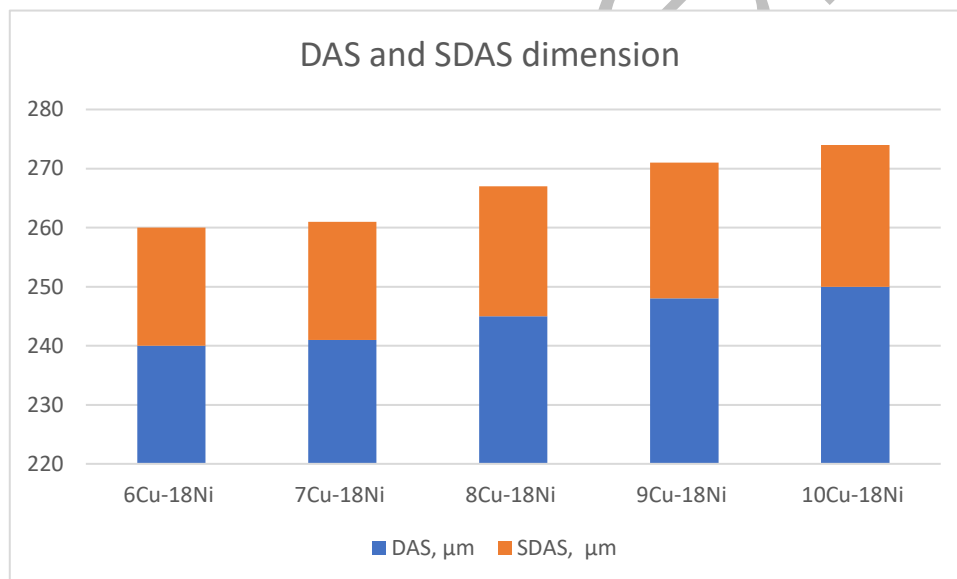


Fig. 6. DAS and SDAS dimension of varying Ni-Resist composition percentage.

3.3 Segregation Behavior and SEM-EDS Analysis

SEM-EDS analysis was used to examine the segregation properties of the modified ductile Ni-resist alloys. Table 2 summarizes a representative compositional analysis of dendritic and interdendritic regions. The findings showed that Ni and Cu partitioned differently during solidification. Because of its strong austenite-stabilizing effect and partition coefficient close to unity, nickel remained relatively uniformly distributed within the γ -austenitic matrix. Cu, on the other hand, showed significant segregation tendencies toward grain boundary and interdendritic areas. The austenitic matrix contained only about 2-4 weight percent Cu, while the interdendritic regions contained about 8–12 weight percent Cu.

The local solidification chemistry was changed by this Cu enrichment, which also increased microstructural heterogeneity. Localized Cu buildup in interdendritic areas altered graphite nucleation conditions and postponed eutectic transformation, which in turn encouraged partial graphite degeneration and decreased nodularity.

Furthermore, localized compositional gradients and more stress concentration sites within the microstructure were caused by Cu segregation in LTF regions. These results are in line with the solidification theory of solute redistribution in multicomponent alloy systems[17], which states that during dendritic growth, elements with partition coefficients less than unity preferentially segregate into the remaining liquid.

The current findings are also consistent with earlier research that found Cu-rich interdendritic segregation in ductile irons with Cu additions above the solubility limit[18]. By directly linking segregation behavior to DAS/SDAS evolution,

graphite morphology degradation, and localized hardness variation in reduced-Ni ductile Ni-resist alloys, the current work expands on earlier findings.

3.4 Phase Stability and XRD Analysis

All alloy compositions maintained a predominantly γ -austenitic structure after solidification, according to X-ray diffraction (XRD) analysis. The (111), (200), (220), and (311) crystal planes were represented by distinctive FCC austenitic peaks in the diffraction patterns displayed in Figure 7. Across all alloy compositions, the calculated γ -Fe content stayed roughly constant at $94.61 \pm 0.1\%$, suggesting that the austenitic matrix could still be stabilized by reducing the Ni content to 18 weight percent and adding Cu up to 10 weight percent.

The identification of the austenitic structure phase is confirmed by the appearance of distinctive peaks from the FCC phase (austenite) at particular 2θ values using X-ray diffraction (XRD). Other peaks are seen, which suggests that alloying has caused a little phase change in the material. XRD offers important information about the crystal structure, phase identification, grain size, stress analysis, and texture of austenitic iron [19]. The face-centered cubic (FCC) crystal structure at room temperature and under typical conditions serves as the basis for phase analysis-based crystal structure identification [24]. The FCC lattice planes are represented by separate peaks in the XRD pattern of an austenitic material (Figure 7). At $43.5^\circ 2\theta$, $50.5^\circ 2\theta$, $74^\circ 2\theta$, and $90^\circ 2\theta$ apiece, these peaks usually contain reflections from planes such as (111), (200), (220), (311), and (222) in the FCC crystal structure. The face-centered cubic (FCC) structure is confirmed by the austenitic phase's peaks, which are usually distinct and crisp in the diffraction pattern.

The strong austenite-stabilizing effect of Ni is the main reason for the stability of the γ -austenitic phase. Although it had less of an impact than nickel, copper also helped stabilize austenite. As a result, the combined Ni–Cu alloying system maintained the FCC matrix structure at room temperature and stopped ferritic transformation during cooling. The XRD patterns showed no discernible secondary phase transformation, indicating that the investigated Cu additions did not destabilize the austenitic phase within the examined composition range. Despite overall matrix stability, localized Cu segregation seen in SEM–EDS analysis suggests that microstructural heterogeneity continued to develop during non-equilibrium solidification.

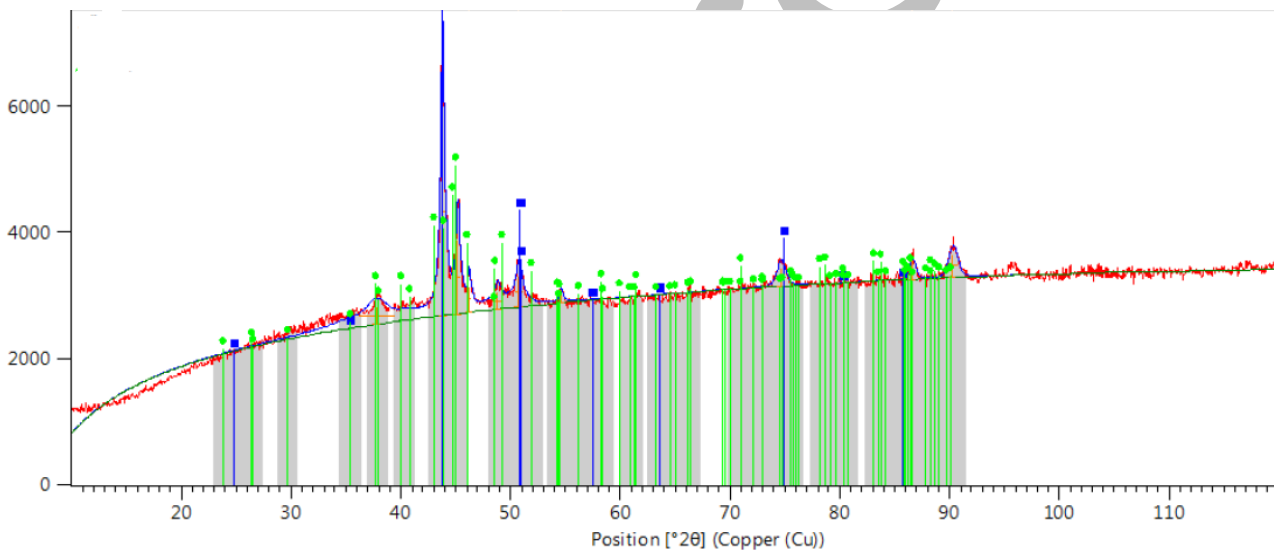


Fig. 7. XRD pattern of alloyed iron.

The SEM-EDS spectrum from the ductile Ni-Resist alloy sample is shown in Figure 8, verifying the distribution and existence of the main alloying and treatment elements. Strong peaks for Fe, Ni, and Cu dominate the spectrum, suggesting that the alloy is mainly made of an iron-based matrix alloyed with notable nickel and copper contents, in line with the desired 6Cu–18Ni to 10Cu–18Ni (wt.%) compositions [20]. The highest intensities are found in iron (Fe) peaks (Fe $L\alpha$, Fe $K\alpha$, and Fe $K\beta$), indicating that Fe is the base element that forms the alloy's matrix. Ni $L\alpha$, Ni $K\alpha$, and Ni $K\beta$ peaks clearly show the presence of nickel (Ni) and confirm its function as a potent austenite stabilizer in Ni-Resist alloys. Additionally visible are copper (Cu) peaks (Cu $L\alpha$, Cu $K\alpha$, and Cu $K\beta$), which verify that Cu was successfully added and dissolved within the alloy system. The formation of a Ni-stabilized austenitic γ -Fe matrix, which is typical of ductile Ni-Resist alloys, is supported by the coexistence of Fe, Ni, and Cu peaks.

Remaining magnesium from the in-mold FeSiMg nodularization treatment is indicated by a clear Mg $K\alpha$ peak. Even though magnesium is mostly used up during graphite spheroidization, traces of it are usually still detectable and show that nodularization was successful. The FeSiMg nodularizer and inoculant additions, as well as potential contributions from the silica-based molding material, are the cause of the prominent Si $K\alpha$ peak. In order to stabilize the ductile iron microstructure and encourage the formation of graphite, silicon is essential. The successful incorporation of all target alloying elements into the Ni-Resist alloy is confirmed by the SEM-EDS spectrum. Within the measurement sensitivity, no unanticipated or harmful impurity elements are found. The effectiveness of the in-mold nodularization and inoculation procedure is confirmed by the presence of Mg and Si. Austenitic dendritic matrices, solute-enriched interdendritic regions,

and stable spheroidal graphite morphology are all supported by the Fe–Ni–Cu elemental combination. Although EDS offers qualitative to semi-quantitative elemental identification, it is unable to address nanoscale microsegregation. Nonetheless, the identified elemental peaks fit in nicely with the microstructural analysis's discussion of dendritic solidification and segregation behavior.

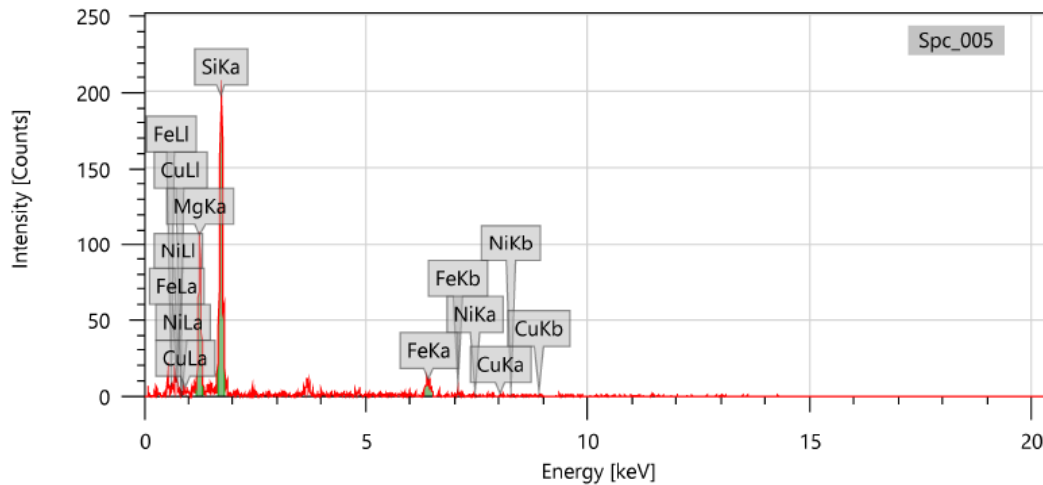


Fig. 8. The ductile Ni-Resist alloy's SEM-EDS spectrum confirms the successful alloying and processing process by displaying dominant Fe, Ni, and Cu peaks along with residual Mg and Si from in-mold nodularization and inoculation treatments.

3.5 Hardness Behavior

Macro-hardness and micro-hardness measurements were used to assess the influence of Cu addition on the mechanical response of the modified ductile Ni-resist alloys. The average macro-hardness increased progressively from 160.0 ± 8.7 HB for the 6Cu–18Ni alloy to 194.3 ± 5.1 HB for the 10Cu–18Ni alloy (Table 5). The increase in hardness is attributed primarily to solid-solution strengthening of the γ -austenitic matrix resulting from Cu dissolution within the Fe-based lattice. Micro-hardness measurements further revealed localized hardness variations within the microstructure. The dendritic cores exhibited an average hardness of 215.7 ± 7.4 HV, whereas the Cu-rich interdendritic and Late-To-Freeze (LTF) regions exhibited significantly higher hardness values of 298.3 ± 1.5 HV. The higher hardness observed in the interdendritic regions is associated with Cu segregation and localized solute enrichment during solidification, which increase lattice distortion and resistance to plastic deformation.

Cu segregation and localized solute enrichment during solidification are responsible for the increased micro-hardness in interdendritic areas. Localized lattice distortion caused by the buildup of Cu and Ni in these areas limited dislocation motion and strengthened resistance to plastic deformation. Additionally, the heterogeneous hardness distribution and localized stress concentration were caused by the presence of coarse dendritic structures and decreased graphite nodularity.

Cu addition increased hardness, but because of the increased microstructural heterogeneity, excessive segregation may have a detrimental effect on ductility and toughness. Therefore, in reduced-Ni ductile Ni-resist alloys, Cu content optimization is required to balance hardness enhancement with graphite stability and segregation control. The strengthening behavior observed is in line with earlier research on Cu-alloyed ductile irons, where Cu served as a solid-solution strengthening element as well as an austenite stabilizer. In low-Ni austenitic ductile iron systems, however, the current study also shows a strong correlation between Cu segregation, dendritic evolution, and localized hardness variation.

Table 5 Macro-hardness and micro-hardness measurements

Materials	Brinell Hardness (HB)	Microhardness (HV)
6Cu-18Ni	160.0 ± 8.7	215.7 ± 7.4
7Cu-18Ni	168.7 ± 4.0	239.0 ± 12.8
8Cu-18Ni	176.3 ± 6.4	275.3 ± 4.5
9Cu-18Ni	189.0 ± 6.2	290.7 ± 5.9
10Cu-18Ni	194.3 ± 5.1	298.3 ± 1.5

4. Conclusions

- XRD analysis revealed that a stable γ -austenitic matrix with roughly 94.61% γ -Fe content was maintained when Cu content was increased from 6 weight percent to 10 weight percent in modified ductile Ni-resist alloys containing 18 weight percent Ni. Increasing Cu addition, however, encouraged interdendritic segregation during solidification, which increased microstructural heterogeneity and affected the growth behavior of graphite.

- As the Cu content increased, the graphite nodularity gradually dropped from $75.1 \pm 0.3\%$ to $71.3 \pm 0.1\%$, and the nodule count dropped from 213.0 ± 1.0 to 201.7 ± 0.6 nodules/mm². All alloys-maintained nodularity values above 70% despite graphite degeneration, indicating the preservation of primarily spheroidal graphite morphology.
- Dendritic coarsening was encouraged by increasing Cu addition; DAS increased from roughly 240 μm to 250 μm and SDAS increased from 20 μm to 24 μm . Cu segregation during the last stages of solidification was confirmed by SEM-EDS analysis, which also showed Cu enrichment in interdendritic and Late-To-Freeze (LTF) regions.
- In contrast to graphite precipitation, the LTF regions showed a stronger propensity for carbide formation and localized enrichment of alloying elements. Increased microstructural heterogeneity and localized hardness enhancement were caused by these separated areas.
- As Cu content rose, macro-hardness increased from 160.0 ± 8.7 HB to 194.3 ± 5.1 HB, and microhardness increased from 215.7 ± 7.4 HV to 298.3 ± 1.5 HV. Cu-induced solid-solution strengthening and segregation strengthening within interdendritic regions are the main causes of the hardness improvement.
- The current results show that microsegregation behavior, dendritic evolution, and graphite morphology during solidification should be taken into account in addition to nominal alloy composition when designing alloys for low-Ni ductile Ni-resist systems. Therefore, achieving a balance between austenitic phase stability, graphite quality, hardness enhancement, and overall microstructural uniformity requires optimizing Cu content.

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Conflict of Interest

The authors declare no conflicts of interest

CRedit of Authors Contribution

M. Aminuddin (Conceptualization, Methodology, Investigation, Writing original draft)

M. Mohd Rashidi¹ (Project administration, Writing-review and editing, Validation, Writing original draft, Supervision)

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References

- [1] N. Fatahalla, A. AbuElEzz, M. Semeida, "C, Si and Ni as alloying elements to vary carbon equivalent of austenitic ductile cast iron: Microstructure and mechanical properties," *Mater. Sci. Eng. A*, vol. 504, no. 1–2, pp. 81–89, 2009. <https://doi.org/10.1016/j.msea.2008.10.019>.
- [2] J. O. Choi, J. Y. Kim, C. O. Choi, J. K. Kim, P. K. Rohatgi, "Effect of rare earth element on microstructure formation and mechanical properties of thin wall ductile iron castings," *Mater. Sci. Eng. A*, vol. 383, no. 2, pp. 323–333, 2004. <https://doi.org/10.1016/j.msea.2004.04.060>.
- [3] W. Xu, [second author], [third author], *et al.*, "Effect of austenitizing temperatures on microstructure and exceptional strength-plasticity synergy in heavy-section pearlitic ductile iron," *Mater. Charact.*, vol. 230, p. 115811, 2025. <https://doi.org/10.1016/j.matchar.2025.115811>.
- [4] C. Pittel, C. Bleicher, K. Lipp, *et al.*, "Production of efficient nodular cast iron gears—Considering the fatigue strength and rolling contact fatigue strength based on the local microstructure," *Int. J. Met.*, vol. 19, pp. 3107–3126, 2025. <https://doi.org/10.1007/s40962-024-01525-z>.
- [5] M. Bork, R. Chulist, M. Górny, M. Kowalczyk, J. Marosz, "The influence of nickel content on the structure parameters and magnetic properties of austenitic ductile iron castings," *Arch. Civ. Mech. Eng.*, vol. 25, no. 3, p. 117, 2025. <https://doi.org/10.1007/s43452-025-01173-y>.
- [6] M. Bork, M. Górny, Ł. Gondek, J. Morgiel, K. Morgiel, "The evaluation of thermal stability, electric conductivity and carbide morphology of austenitic ductile iron castings," *Materials*, vol. 18, no. 20, p. 4734, 2025. <https://doi.org/10.3390/ma18204734>.
- [7] K. I. Yaakob, M. R. Maarof, M. A. Rosnizan, "Evaluation of elevated temperature oxidation of higher manganese Ni-resist alloy," *J. Adv. Res. Fluid Mech. Therm. Sci.*, vol. 122, no. 2, pp. 52–61, 2024. <https://doi.org/10.37934/arfmts.122.2.5261>.

- [8] A. Vaško, V. Zatkalíková, M. Uhrčík, V. Kaňa, "Corrosion resistance of austenitic NiMn-nodular cast iron in NaCl solution," *Arch. Metall. Mater.*, vol. 69, no. 3, pp. 1115–1122, 2024. <https://doi.org/10.24425/amm.2024.150932>.
- [9] S. Xiang, S. Jonsson, R. P. Babu, B. Zhu, J. Odqvist, "Influence of tension and compression dwell on the creep-fatigue properties of the austenitic cast iron Ni-resist D5S," *Mater. Sci. Eng. A*, vol. 814, p. 141179, 2021. <https://doi.org/10.1016/j.msea.2021.141179>.
- [10] X. Wang, B. Jiang, C. Yang, *et al.*, "Effects of Ni addition on the microstructure and low-temperature impact behavior of ductile iron after ferritization treatment," *Mater. Today Commun.*, vol. 50, p. 114513, 2026. <https://doi.org/10.1016/j.mtcomm.2025.114513>.
- [11] G. A. Çelik, M.-I. T. Tzini, Ş. Polat, Ş. H. Atapek, G. N. Haidemenopoulos, "Thermal and microstructural characterization of a novel ductile cast iron modified by aluminum addition," *Int. J. Miner. Metall. Mater.*, vol. 27, no. 2, pp. 190–199, 2020. <https://doi.org/10.1007/s12613-019-1876-8>.
- [12] S.-Y. Shin, S.-H. Ha, D.-H. Kim, J. Choi, "Effect of Cu addition above the solubility limit on microstructure formation and Cu segregation in 800 MPa grade ductile cast iron during solidification," *Arch. Metall. Mater.*, vol. 69, no. 2, pp. 425–428, 2024. <https://doi.org/10.24425/amm.2024.149759>.
- [13] M. M. Rashidi, M. H. Idris, "The effects of solidification on the microstructure and mechanical properties of modified ductile Ni-resist iron with a high manganese content," *Mater. Sci. Eng. A*, vol. 597, pp. 395–407, 2014. <https://doi.org/10.1016/j.msea.2013.12.070>.
- [14] J. Tlatlik, J. Hohe, I. Varfolomeev, "Composite descriptors for cast iron microstructures: A data-driven approach to understanding microstructure–property relationships," *Eng. Fract. Mech.*, vol. 330, p. 111655, 2025. <https://doi.org/10.1016/j.engfracmech.2025.111655>.
- [15] C. Öberg, R. Rablbauer, B. Zhu, S. Jonsson, "Monotonic and cyclic creep of cast materials for exhaust manifolds," *SAE Int. J. Mater. Manuf.*, vol. 12, no. 2, pp. 149–162, 2019. <https://doi.org/10.4271/05-12-02-0012>.
- [16] G. Di Egidio, P. Ferro, A. Morri, "Microstructure in non-standard heavy section ductile iron castings: Influence of solidification time and casting size," *J. Iron Steel Res. Int.*, vol. 32, no. 12, pp. 4249–4263, 2025. <https://doi.org/10.1007/s42243-025-01598-y>.
- [17] Y. Xu, Y. Xu, W. Cao, X. Meng, F. Zhang, X. Lv, "Effect of solute elements (B, C, N, O) on γ -Fe $\Sigma 5$ (210)[001] grain boundary: A first-principles study," *J. Iron Steel Res. Int.*, vol. 32, no. 6, pp. 1716–1724, 2025. <https://doi.org/10.1007/s42243-025-01436-1>.
- [18] S. N. Lekakh, M. Li, L. Godlewski, "High-temperature performance of alloyed cast irons and Cr/Ni austenitic steels—An overview and discussion," *Int. J. Met.*, vol. 20, no. 4, pp. 2114–2132, 2026. <https://doi.org/10.1007/s40962-025-01775-5>.
- [19] M. Górny, G. Angella, K. Jalava, Ł. Gondek, J. Marosz, B. Cygan, "The effect of austenitization on ausferrite stability and section sensitivity of Ni and Cu alloyed austempered ductile iron," *Mater. Today Commun.*, vol. 54, p. 115606, 2026. <https://doi.org/10.1016/j.mtcomm.2026.115606>.
- [20] M. Lanchas, D. O. Ferdinando, J. Massone, R. Boeri, "Revealing, modification and influence of the austenitic grain size on the solid-state transformations in ductile iron," *Int. J. Met.*, vol. 19, no. 6, pp. 3378–3391, 2025. <https://doi.org/10.1007/s40962-025-01547-1>.