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Strength Characteristics of Inoculated and Nodularised Thin Wall Ductile Iron Castings

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Abstract

Carbide precipitates in Thin Wall Ductile Iron (TWDI) used for automotive applications needs to be eliminated or reduced for improved strength, ductility, crack propagation resistance and good machinability. Ductile iron thin section profiles (≤3 mm) present danger of massive carbide precipitations in the as-cast sample. Precipitated carbide phase is brittle and negatively affects the mechanical properties of the iron matrix. The suppression of carbide formation is associated with the nucleating properties of the nodularizer and innoculant alloys. This treatment is vital in ensuring that carbide precipitation, flake graphite structure and non-nodular graphite phases are reduced or completely eliminated in the TWDI castings. Therefore, the temperature and technique of treatment would influence the yield of the process, and ultimately the mechanical properties. In this study, the effect of nodularization and inoculation treatment temperature on the microstructure and mechanical properties of TWDI castings is examined. The results indicate that good nodularity and nodule count with better percent elongations are achieved using low treatment temperatures in descending order of 1490˚C, 1470˚C and 1450˚C, but have negative effect at lower treatment temperature of 1430˚C. However, TWDI castings have superior properties in terms of nodule counts and nodularity at 1450˚C. Treatment temperature does not produce significant influence on ultimate tensile strength (UTS) and hardness of TWDI castings. TWDI castings show poor nodularity, nodule count and ductility at higher inoculation treatment temperatures of 1550˚C, 1530˚C and 1510˚C.

Keywords

Thin Wall Ductile Iron (TWDI), Nodularization, Inoculation, Graphite Structure

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1. Introduction

In the production of sound Thin Wall Ductile Iron (TWDI) castings, adequate melt treatment involving efficient inoculation and nodularization are imperative. There should be synergy between these two important treatments for the production of good nodularity, high nodule count and carbide free TWDI. Nodularization treatment is carried out first and followed by a two step inoculation treatment. Nodularization treatment is a modification treatment where the shape of the graphite is changed from flake to spheroid or nodules. This shape is responsible for the peculiar properties of ductile iron. Inoculation is followed immediately to facilitate heterogeneous nucleation for increase nodule count and suppression of carbide formation. Prior to the nodule treatment, it is important to ensure the melt is very low in sulphur ($0.01\% \le S \le 0.03\%$). The ferroalloys of ferrosilicon-magnesium and ferrosilicon used for these treatments have fading tendencies. Thus, the melt have to be poured into the mould within a maximum period of seven minutes after the nodularization treatment is done or the treatments would be ineffective. Temperature and treatment technique would affect nodularity and nodule count which in turn influences mechanical properties. The suppression of carbide formation is associated with the nucleating properties of the nodularizer and innoculant alloys. The nucleating property is understood as the number and potency of nuclei formed by the alloy addition. The nodularizer and innoculant additions also influence ductile iron solidification shrinkage [1].

Ductile Iron application for lightweight components is being limited by inability to produce as-cast carbide free thin (≤3 mm) wall parts [2]. This inability results from the formation of large volumes of carbide precipitates, poor nodularity and nodule count, presence of non-nodular graphite structures and undesired matrix types in the cast TWDI part. Borrajo *et al*. [3] observed appreciable increase in nodule count when cooling rate increased, as a consequence of the thin walls. The observation is possible because of the under-cooling that takes place during solidification of the thinner sections, which activates a larger number of substrates for heterogeneous nucleation of graphite.

The fast cooling of thin section ductile iron castings requires special consideration to produce carbide-free castings [4]. The common feature that all ductile irons share is the spherical shape of the graphite nodules. These graphite nodules are nucleated on small inclusions during solidification [5]. The relative possibilities for nucleation and growth depend upon foreign particles in the melt, whether as trace impurities or as deliberate additions [6]. The amount and form of graphite in ductile iron are determined during solidification and cannot be altered by subsequent heat treatment. The principal factor in determining the different grades of ductile iron in specifications is the matrix structure [7]. In the as-cast condition the matrix will consist of varying proportions of pearlite and ferrite, these can be further altered by heat treatment.

Pouring very thin sections ductile iron presents danger of massive carbide precipitation [8]. The time after spheroidal treatment (holding time) has significant effect on the elongation, but negiligble effect on the tensile strength and hardness of TWDI castings. The graphite shape is also influenced by the holding time [7]. The wall thickness of spheroidal graphite cast iron has very strong effect on the graphite size and shape of the castings [9].

Bockus and Dobrovolskis [10] studied production of ferritic ductile iron castings. The result shows that it is very difficult to obtain thin section of ferritic ductile iron as-cast, as it is associated with high solidification rate and formation of carbides. The investigation reveals that ductile iron castings will be ferritic (as-cast) only when large amounts (more than 50 percent) of pig iron are used in the charge.

In the production of quality cast irons the inoculation process is of vital importance. When comparing un-inoculated and inoculated irons, differences in microstructure are easily revealed with strong effect on the final mechanical properties of the casting. Through inoculation the graphite nucleation and eutectic under-cooling of the iron can be controlled and this will be of crucial importance in giving the iron its required service properties [11]. Inoculation introduces additional nuclei which cause graphite precipitation and reduces the under-cooling and formation of carbides [12].

Works on composition, [13]-[16], treatment techniques [7] [12] and [17] and frequency [18] have been carried out to determine the best way to carry out these treatments. However, earlier studies lacked information on the appropriate temperature at which the nodularization treatment should be done for best yield and magnesium recovery.

This study presents a molten metal processing technique for treatment temperature that eliminates primary carbides and non-nodular graphite structures in pearlitic-ferritic ductile iron castings useful for automotive applications.

2. Experimental Methodology

Seven treatment temperatures namely 1550˚C, 1530˚C, 1510˚C, 1490˚C, 1470˚C, 1450˚C and 1430˚C are studied to determine best properties and microstructure. The charge materials consist of mild steel scraps, ductile iron returns, ferrosilicon and graphite as shown in **Table 1**. The requirements of ASTM E2349 standard mould making procedures are employed using adequate moulding equipment to produce dense moulds. The moulding sand consists of silica sand, bentonite, additives (coal dust and starch) and water. The dimensions of the drag and cope are 410 mm × 375 mm with a height of 110 mm. The patterns for the cavity, runners and in-gates are placed in the drag section and rammed adequately while the sprue pattern of height 100 mm is placed in the cope. The pressurized casting technique is used with ratio of 3:2:1 which translates to cross sectional area at sprue: cross sectional area at runner: cross sectional area at ingate.

The molten metal is first tapped at 1555˚C into a preheated treatment ladle for the first treatment temperature of 1550˚C using the sandwich method. The treatment alloy used 12 - 16 mm ferrosilicon magnesium granules covered with steel scraps and placed at the bottom of the ladle. This same procedure is repeated for treatment temperatures of 1530˚C tapped at 1535˚C, 1510˚C tapped at 1515˚C, 1490˚C tapped at 1495˚C, 1470˚C tapped at 1475˚C, 1450˚C tapped at 1455˚C and 1430˚C tapped at 1435˚C. The treated molten metal are then transferred into the pouring ladle where the first inoculation treatment occurs in the melt stream. The second inoculation treatment is done on the melt stream during discharge into the moulds. The samples are labeled as shown in **Table 2**. These procedures are maintained for all the treatment temperatures and moulds were cast within six minutes after treatment to avoid fading of inoculants.

2.1. Hardness Test

Brinel hardness test is carried out using a 10/3000 kg indentation ball on tester model Foundrax/B.H.D/1003402.

2.2. Tensile Test

A computerized universal mechanical testing machine, instron series 3369 is used to determine tensile properties in accordance with ASTM E8 standard. The dimension of test piece is shown in **Figure 1**.

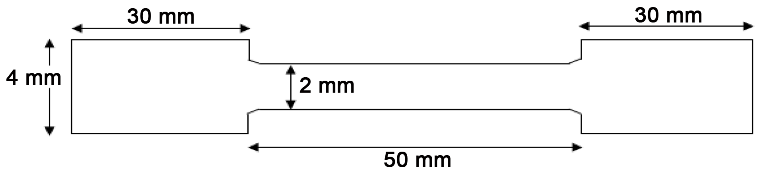


Figure 1. Dimension of tensile test sample.

Table 1. Chemical composition of charge materials.

Charge	Weight % (kg)	Charge %	C (Charge Comp.) %	Si (Charge Comp.) %	Mn (Charge Comp.) %
Mild Steel	320	64	0.1	0.1	0.2
Ductile Iron Returns	150	30	0.1	0.1	0.2
Ferro-Silicon	7	1.4	0.0	70	0.0
Graphite	23	4.6	70	0.0	0.0

Table 2. Sample designation and treatment temperature.

S/N Treatment	1	2	3	4	5	6	7
Temperature, ˚C	1550	1530	1510	1490	1470	1450	1430
Sample Name	T1	T2	T3	T4	T5	T6	T7

2.3. Morphological Analysis

Samples for microstructural analysis are cut, ground progressively using 180, 240, 320, 400 and 600 abrasive papers. These are then polished using silk cloth charged with 3 µm diamond paste according to standard procedure outlined in ASTM Standard E 3 for metallographic analysis. The prepared samples are viewed in their unetched and etched (using 2% nital solution) conditions using a CETI Optical Metallurgical Microscope Model No. 0703552 at magnification of 100×.

3. Results and Discussion

3.1. Effect of Treatment Temperature on Hardness Responses of TWDI

The hardness trend of TWDI with treatment temperatures used is shown in **Table 3** and **Figure 2**. The trend is not uniform, but superior hardness is obtained at lowest temperature of 1450˚C for 2, 3 and 4 mm thick samples, while 1550˚C have the lowest values.

3.2. Effect of Treatment Temperature on Tensile Strength of TWDI

Figures 3-5 show the patterns of Ultimate tensile stress, percent elongation and percent elongation at UTS respectively with treatment temperature. In **Figure 3**, the sinusoidal UTS pattern have peak UTS of 389, 409 and 514 MPa for 2, 3 and 4 mm thicknesses respectively, achieved at 1450˚C which corresponds to the second lowest treatment temperature after 1430˚C which is the lowest treatment temperature used. This indicates that low treatment temperature of 1450˚C (tapped at 1455˚C) is important to achieve the best UTS value for the nodularization treatment reaction but treating at temperature lower than this (1430˚C) can negatively affect UTS.

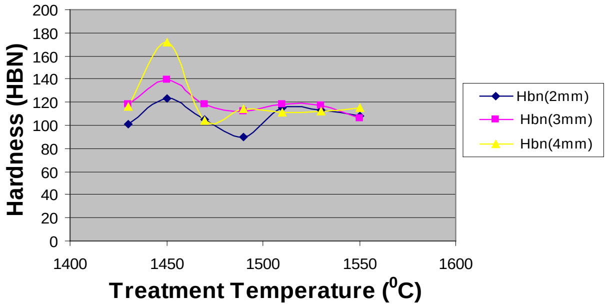


Figure 2. Hardness behaviour of TWDI with treatment temperature.

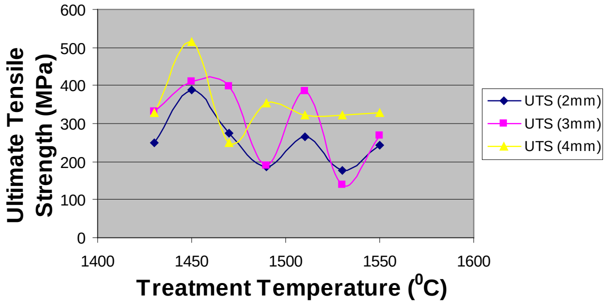


Figure 3. UTS of TWDI castings with treatment temperature.

Table 3. HBN values of cast samples with treatment temperature.

Treatment Temperature (˚C)	1430	1450	1470	1490	1510	1530	1550
HBN (2 mm)	101	123	105	90	115	113	108
HBN (3 mm)	118	139	118	112	118	117	106
HBN (4 mm)	116	172	104	114	111	112	115

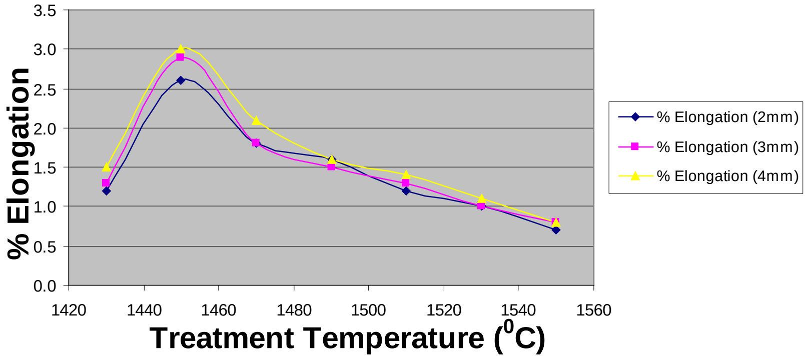


Figure 4. Percent elongation of TWDI castings with treatment temperature.

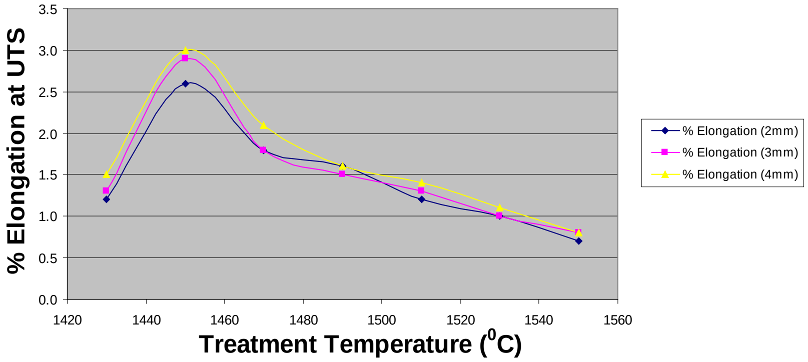
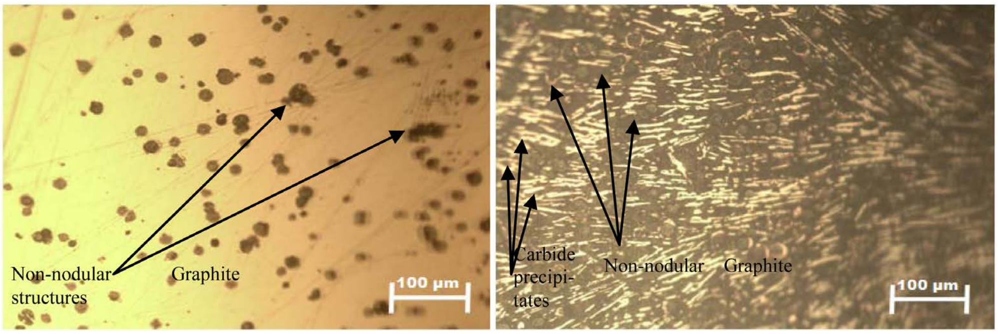


Figure 5. Percent elongation at UTS of TWDI castings with treatment temperature.

The percent elongation as shown in **Figure 4** has a defined pattern with treatment temperature significantly imacting on ductility. Treatment temperature of 1550˚C results in percent elongations of 0.7, 0.8 and 0.8 for 2, 3 and 4 mm thicknesses respectively. In the treatment temperature of 1450˚C, percent elongation improved significantly to 2.6, 2.9 and 3.0 for 2, 3 and 4 mm respectively. This indicates that low treatment temperature of 1450˚C favours better nucleation of graphite structures, better nodule count and nodularity. These three parameters have direct bearing on ductility. The best ductility of 2.6, 2.9 and 3.0 is achieved at 1450˚C for all the three thicknesses investigated. Treatment at 1430˚C had negative effect on nodule count and nodularity as is seen from the lower percent elongation values observed for the three thicknesses (1.2, 1.3 and 1.5).

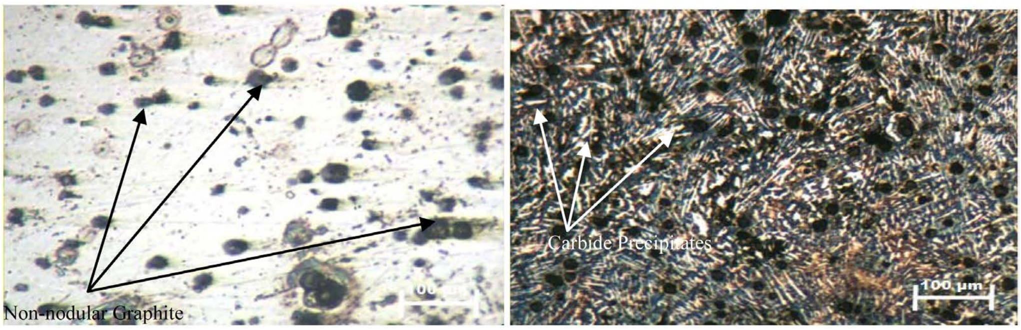
3.3. Effect of Treatment Temperature on Morphology of TWDI

The microstructures of samples TI (2, 3, 4 mm) **Figures 6-8** show the existence of irregularly-shaped (non-nodular) graphite structures resulting in poor nodularity, low nodule count with carbide precipitates in the etched micrograph. Thus, the yield of the treatment at the treatment temperature of 1550˚C is greatly impaired. The T2 range of samples, **Figures 9-11** also show the same trend. In T2, 2 mm section sample shown in **Figure 9**, in addition to poor nodule count and nodularity, shows the existence of shrinkage porosity in its structure. This is due to insufficient nuclei for the precipitation of graphite structures. The carbide phase in the T3 range reduces compared to the T1 and T2 samples in **Figures 12-14**. The T3, 2 mm sample also shows the presence of non-nodular graphite structures and carbide precipitates. In T3, 3 mm the matrix contains large proportion of irregular shaped graphite structures. Improved nodularity, nodule count and reduction of the carbide phase are observed for T4 - T6 range of samples in **Figures 15-23**. The best morphologies are achieved for the T5 (1470˚C) and T6 (1450˚C) samples, where good nodularity of graphite sizes 5, 6 and 7, high nodule count and absence of carbide precipitates are observed in pearlite-ferrite matrix. This structure explains the earlier superior hardness, UTS and percent elongation values obtained and shown in **Figures 2-4**. A lower treatment temperature of 1430˚C obviously had negative effect on microstructure of TWDI as seen in **Figures 24-26** where carbide precipitates and non-nodular graphite structures is evident. This structure explains the drop in percent elongation in **Figure 4**.



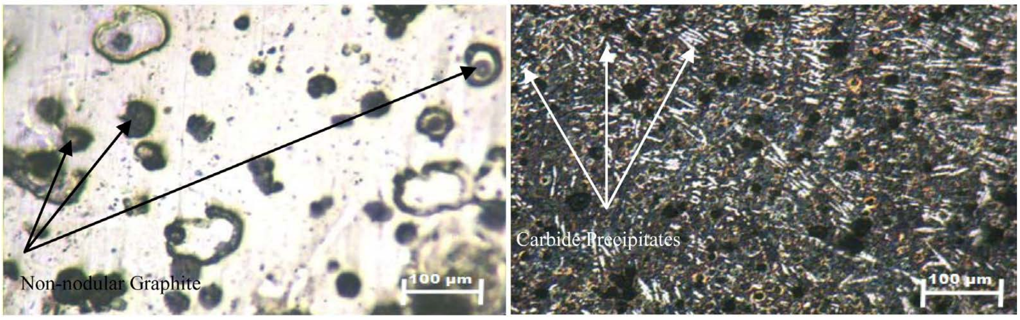
(a) (b)

Figure 6. Micrographs of 2 mm T1 sample (a) Unetched and (b) Etched.



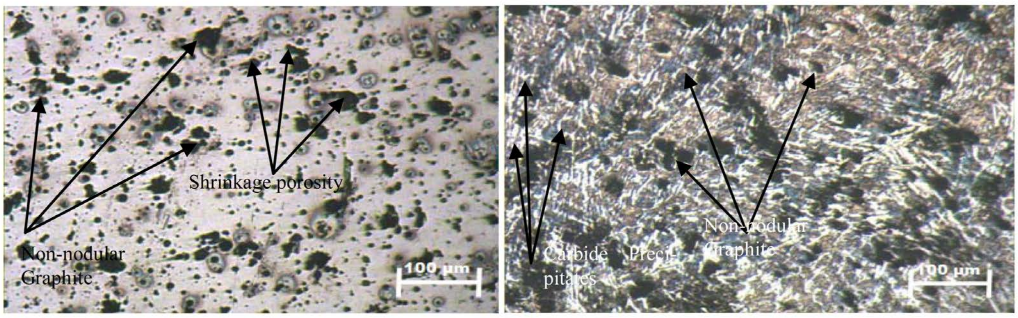
(a) (b)

Figure 7. Micrographs of 3 mm T1 sample (a) Unetched and (b) Etched.



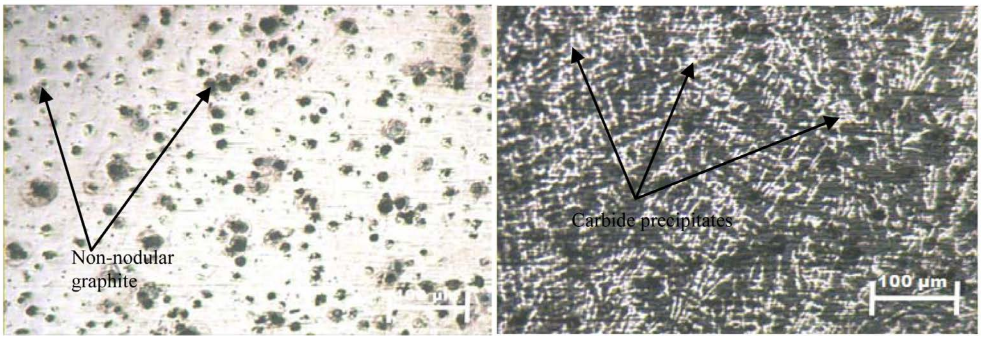
(a) (b)

Figure 8. Micrographs of 4 mm T1 sample (a) Unetched and (b) Etched.



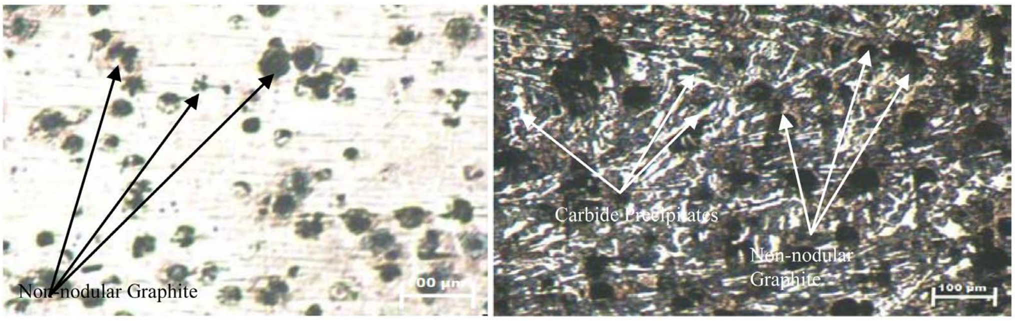
(a) (b)

Figure 9. Micrographs of 2 mm T2 sample (a) Unetched and (b) Etched.



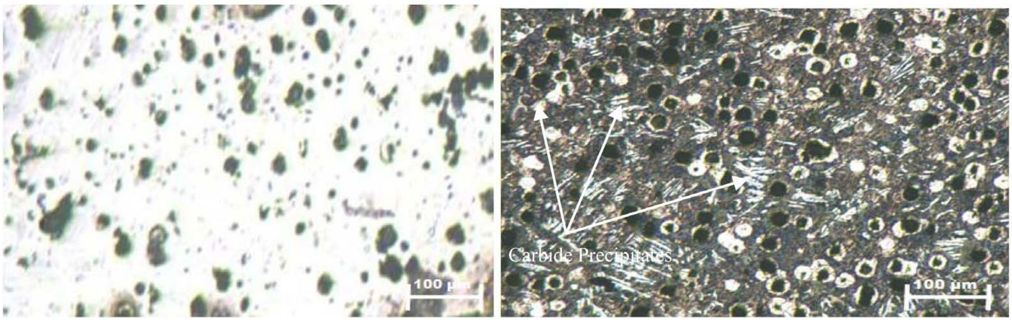
(a) (b)

Figure 10. Micrographs of 3 mm T2 sample (a) Unetched and (b) Etched.



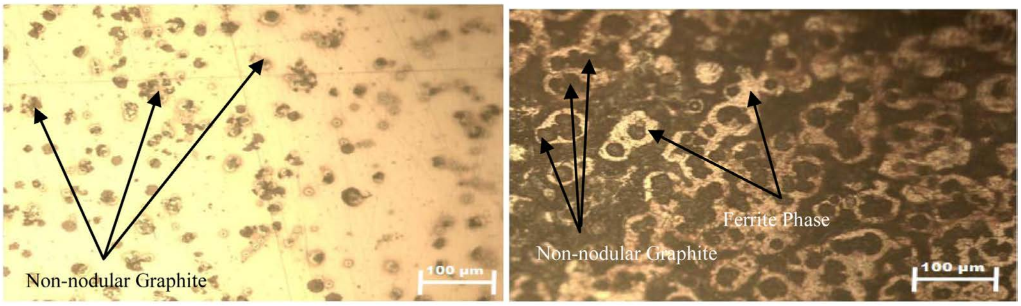
(a) (b)

Figure 11. Micrographs of 4 mm T2 sample (a) Unetched and (b) Etched.



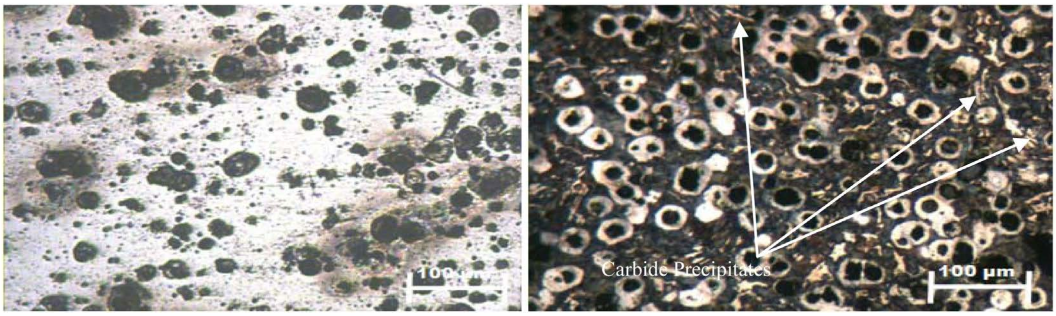
(a) (b)

Figure 12. Micrographs of 2 mm T3 sample (a) Unetched and (b) Etched.



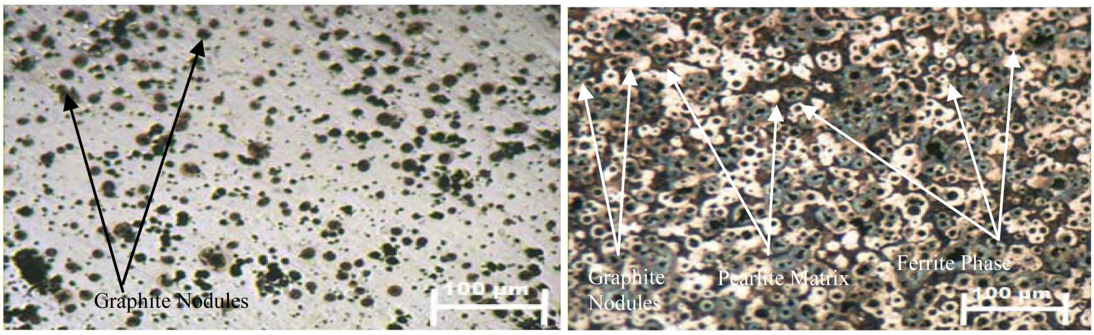
(a) (b)

Figure 13. Micrographs of 3 mm T3 sample (a) Unetched and (b) Etched.



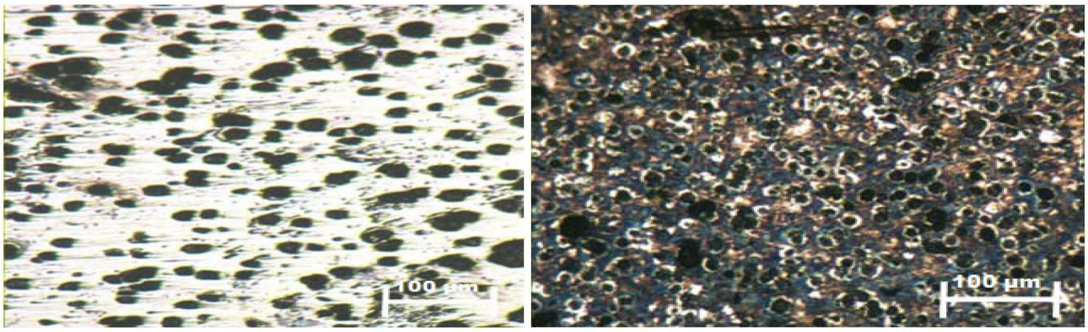
(a) (b)

Figure 14. Micrographs of 4 mm T3 sample (a) Unetched and (b) Etched.



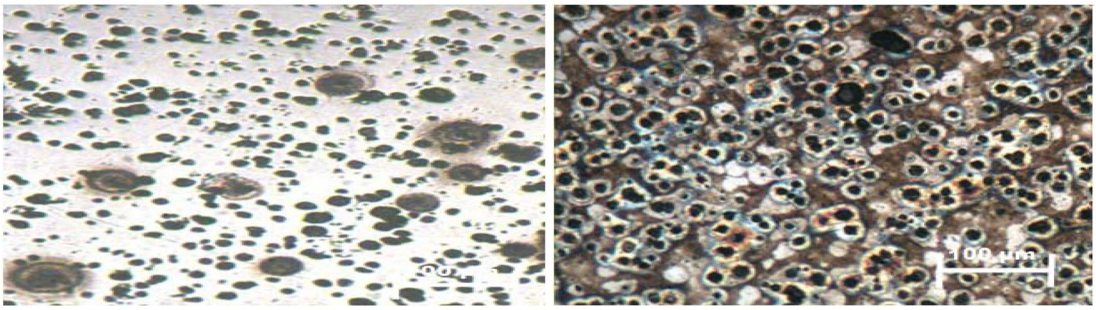
(a) (b)

Figure 15. Micrographs of 2 mm T4 sample (a) Unetched and (b) Etched.



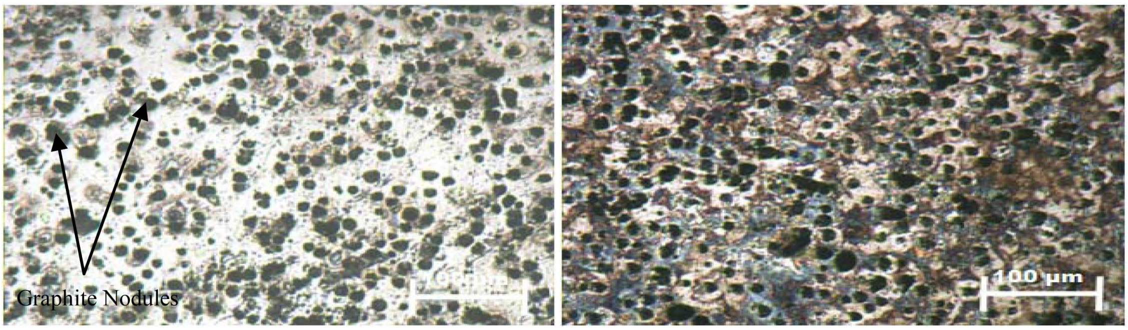
(a) (b)

Figure 16. Micrographs of 3 mm T4 sample (a) Unetched and (b) Etched.



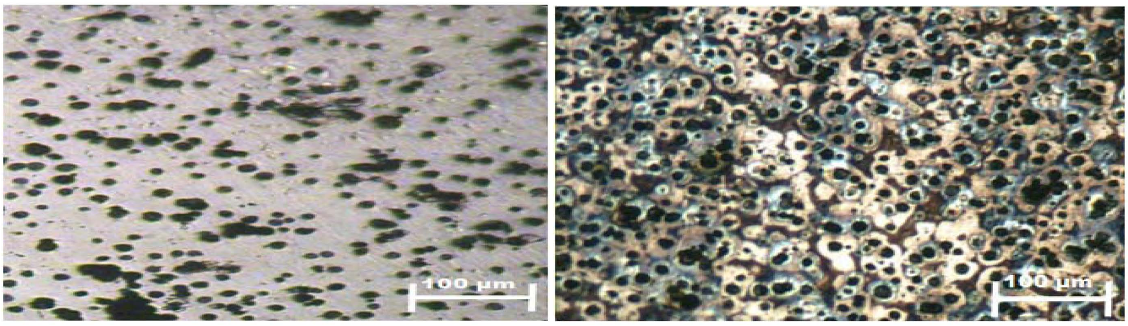
(a) (b)

Figure 17. Micrographs of 4 mm T4 sample (a) Unetched and (b) Etched.



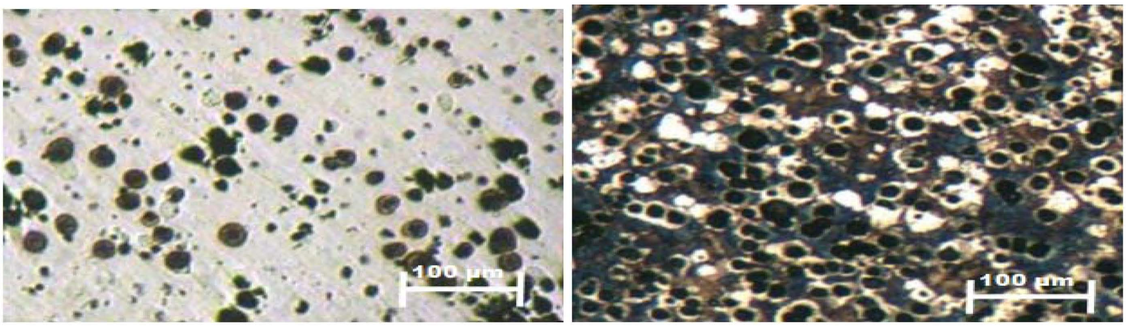
(a) (b)

Figure 18. Micrographs of 2 mm T5 sample (a) Unetched and (b) Etched.



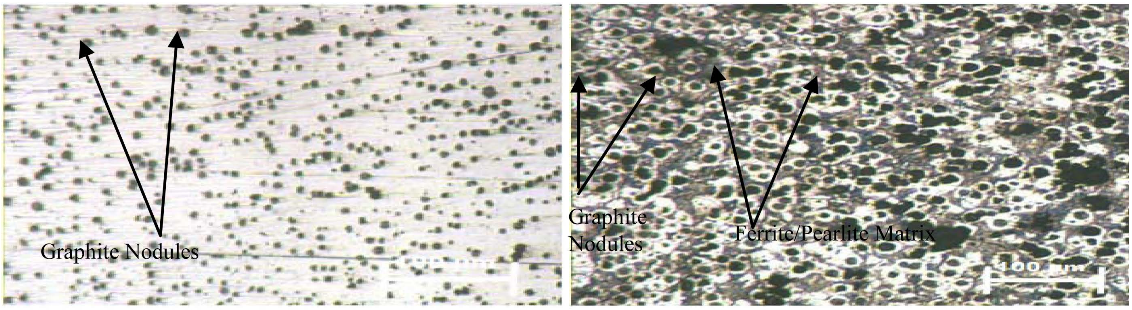
(a) (b)

Figure 19. Micrographs of 3 mm T5 sample (a) Unetched and (b) Etched.



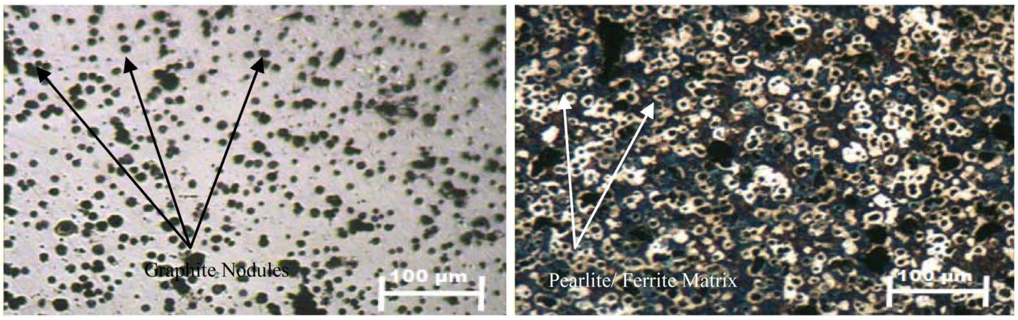
(a) (b)

Figure 20. Micrographs of 4 mm T5 sample (a) Unetched and (b) Etched.



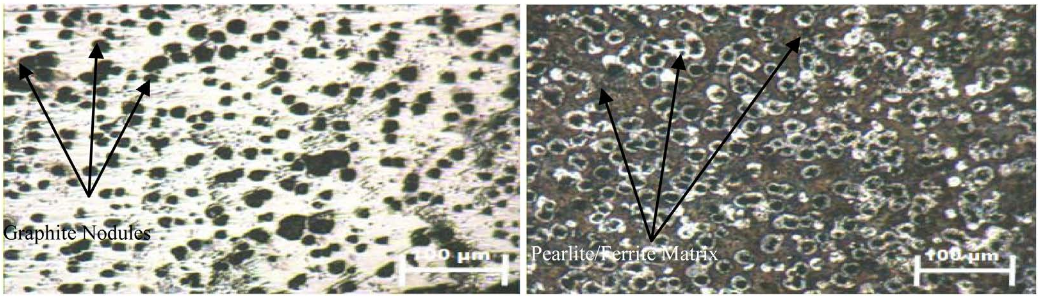
(a) (b)

Figure 21. Micrographs of 2 mm T6 sample (a) Unetched and (b) Etched.



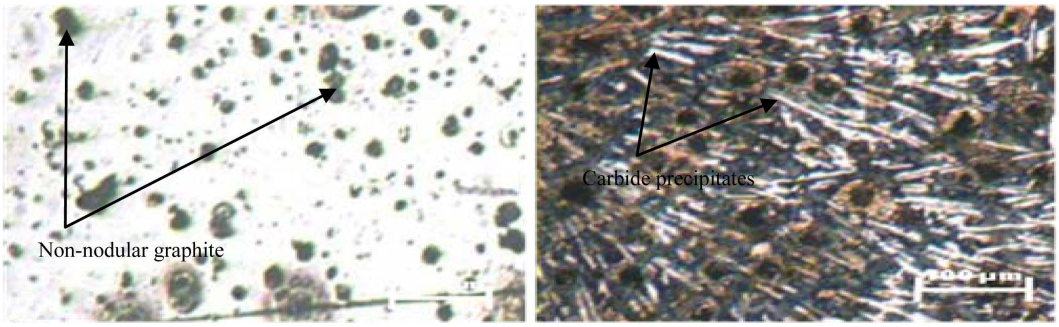
(a) (b)

Figure 22. Micrographs of 3 mm T6 sample (a) Unetched and (b) Etched.



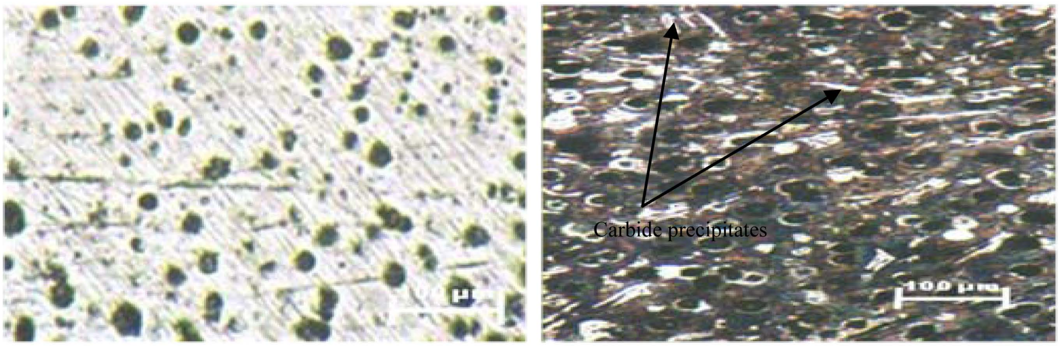
(a) (b)

Figure 23. Micrographs of 4 mm T6 sample (a) Unetched and (b) Etched.



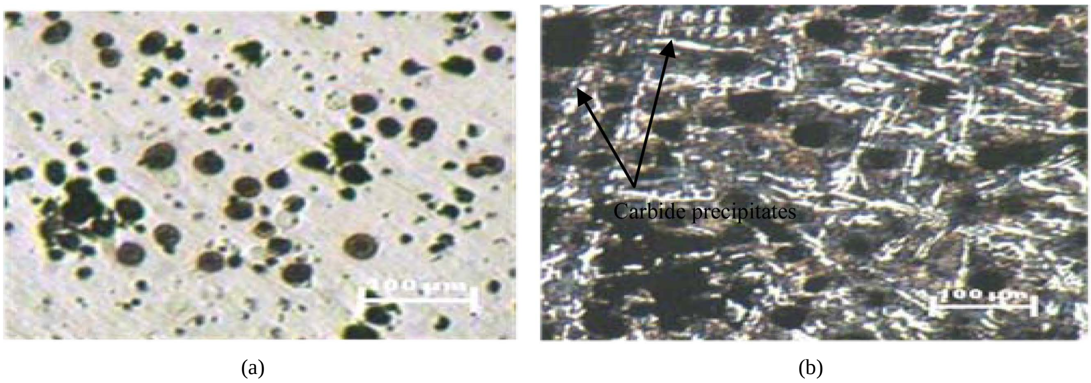
(a) (b)

Figure 24. Micrographs of 2 mm T7 sample (a) Unetched and (b) Etched.



(a) (b)

Figure 25. Micrographs of 3 mm T7 sample (a) Unetched and (b) Etched.



(a) (b)

Figure 26. Micrographs of 4 mm T7 sample (a) Unetched and (b) Etched.

4. Conclusions

This study has shown that it is possible to obtain carbide free, good nodularity and nodule count in thin wall ductile iron castings through in ladle sandwich nodularization treatment method accompanied by two step inoculation treatment.

Lower treatment temperatures of 1450˚C and 1470˚C promote magnesium recovery, better microstructure and mechanical properties, but treatment temperature as low as 1430˚C is unfavourable as mechanical properties became significantly impaired. The higher temperatures of 1530˚C and 1550˚C produce unfavourable microstructure and poor mechanical properties.

Treatment temperature of 1450˚C results in carbide free matrix, good nodularity and nodule count structure with 123, 139 and 172 HBN, 389, 409 and 514 MPa tensile strengths, 2.6%, 2.9% and 3.0% elongation for 2, 3 and 4 mm thick samples respectively.

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