OPTIMIZATION OF STRUCTURE-PROPERTY OF THIN WALL AUSTEMPERED DUCTILE IRON

Saroj Kumar[1], D. J. Gawai,[1] D. N. Prasad[2] and K. K. Singh[3#]

1 -M. Tech students, 2- Professor, Dept of Foundry Technology, 3- Associate Professor, Dept. of Foundry Technology, National Institute of Foundry and Forge Technology, Ranchi

Corresponding author, E-mail- kksingh_nifft@yahoo.com

Many cast parts are currently produced in Aluminum rather than cast iron, because of the drive to get high strength /weight ratio for application in automobile and aerospace. Ductile Iron casting of approximately 2-3mm section thickness better known as Thin wall ductile iron (TWDI) having high strength /weight ratio and better mechanical properties than Aluminum alloys. The austempering treatment of these TWDI components may further lead to improvement in the strength/weight ratio and will be a suitable and economical alternative to use in automobile parts.

The effect of various parameters like, gating and feeding, pouring temperature, post inoculation on the structure and properties of TWDI were studied and it was observed that for a thin plates decreasing in pouring temperature leads to finer pearlitic structure and increase in hardness. The increase in inoculation percentage leads to increase in the nodule count, decrease in nodule size and increase in volume fraction of ferrite. Gating and feeding design effect was analysed by using simulation software "ProCAST" and actual casting. It was found that the casting with suitable design and location of riser eliminates the formation of chills and reduces the difference in nodule count at various sections. As expected the hardness increased with decrease in section thickness.

Short term austempering treatment was used to obtain thin wall ADI castings. The samples of 2 and 3 mm thickness were austenitized at 900 °C for, 30 minutes followed by holding at 350°C, 400°C and 450°C for 5, 15, 30 and 60 minutes for each temperature. The microstructures and mechanical properties were analyzed in respect of various process parameters like austempering time, austempering temperature and section thickness.

Introduction

Unlike gray iron whose production tends to stagnate, ductile iron enjoy growth exceeding 3% per year[1]. In the recent years there has been an increasing interest in minimizing the weight of casting components for example by reducing the wall thickness and by using hollow sections and ribs to increase the stiffness of the components [2]. Currently the substitution of aluminum for cast iron and steel, and magnesium for aluminum is continuing. The use of aluminum, however results in higher vehicle costs as the higher cost of Al. alloys and also energy requirement for melting of aluminum are higher than those for cast iron (1100 kwh/ton for aluminium vs. 600 kwh/ton for iron). For the production of large amount of light parts it should have high strength and stiffness, be of low density and very important must produced in large quantities at low costs. Ductile iron can be produced by casting in large amount at low cost. It has high stiffness, good ductility, resistance to shock, and it can reach very high strength by heat treatment, thus it satisfy many design requirements for automobile application[3,4]. High density and difficult to shape into thin section are the two major problems limit ductile iron application to light parts [5]

Producing light weight ductile iron casting by reducing the thickness of casting to approximately 2-3mm with high strength/weight ratio and better mechanical properties make thin wall Ductile iron casting (TWDI) an economical alternative to cast Aluminium components. It also makes possible the conversion of many steel assemblies to ductile iron due to its yield stress/cost ratio. The solidification behavior of TWDI casting where studies by Several Investigators [6-14]. They observed the directional growth of dendrites and graphite spheroids in the thin section. T. Kanno et.al[13]. found that with increase in pouring temperature, the nodule count decrease and the nodule become larger while the volume shrinkage cavities also increases. L.P. Dix et.al[4] demonstrated the effect of various parameters on the mechanical properties of thin walled ductile iron castings. Cooling rate during solidifications has a significant influence on ductile iron nodule count. Faster cooling rate results in higher nodule count.

The successful production of ADI requires both adequate foundry process controls to produce a consistent high quality ductile iron that will respond to austempering heat treatment for the attainment of desired mechanical properties. Austempering should not be thought as medium to improve the properties of inferior quality castings, rather requires attention to produce a material having much superior properties than ductile iron. Production of good quality ductile iron is the primary step followed by austempering to get the desired properties of ADI. This is done either in a non-oxidising atmosphere furnace or in a high temperature salt bath. Temperatures and times are determined by chemical composition, section size and grade of ADI required. Slow initial heating of the casting is desirable to avoid the danger of cracking of complex shapes. The castings are then quenched to the required isothermal heat treatment temperature, usually between 230^0C and 450^0C [15]. Austempering should be completed in a salt bath made up of KNO_3, $NaNO_2$ and $NaNO_3$ in the ratio 55 to 40 to 5 [16]. Mixtures of sodium nitrite, sodium nitrate and potassium nitrate are used as a heat transfer medium which melts at 143^0C and can be used at temperatures of up to 550^0C [17]... The effect of various process variable as compositional variables heat treatment variables and section thickness on the structure-property of ADI were studied by several investigators [18-28].

2.0 EXPERIMENTAL DETAILS

To study the effect of process parameters of austempered thin wall ductile iron, the experimental procedure adopted is briefly described in three different sections as: Production of ductile iron castings, heat treatment of cast samples and properties evaluation.

2.1 PRODUCTION OF THIN WALL DUCTILE IRON CASTING:

To obtain the thin wall ductile iron (TWDI) castings, the heat were taken in Induction furnace (capacity 1 ton) at a foundry unit. Liquid metal was tapped into the hot ladle at 1460^0C-1510^0C. The final chemistry of heat was obtained by spectrometer as given in Table 1.

Table.1: Charge Chemistry for heat:

Elements	C	Si	Mn	P	S	Cr
Wt %	3.75	2.65	0.39	0.096	0.012	0.04

To get different section thickness plates (2mm, 3mm and 5mm) and step bars, without riser and with riser, CAD model was made using CATIA .The test casting has a plate shape with dimensions of 150 mm x 50 mm and 2, 3 and 5 mm thickness.

Jolting and squeezing molding machine was used to produce mold. The patterns plates and moulds obtained for the case having no riser and other case having riser are shown in Fig. 1& Fig. 2 respectively. The fluid flow and thermal analysis was done using ProCAST software.

(a) (b)

Fig.1: Pattern layout and mould of casting without riser

(a) (b)

Fig.2: Pattern layout and mould of casting with riser

2.2 HEAT TREATMENT OF CAST SAMPLES:

In Heat Treatment cycle I , Step bar of steps 14, 11, 6 and 3mm were austenitized at room temperature to 880^0C for 30 minutes in a heating muffle furnace at a rate of 50-60^0C/hr. Then the furnace was cooled to 450^0C and soaked for 5 hours. After soaking sample was oil quenched as shown in Fig.3.

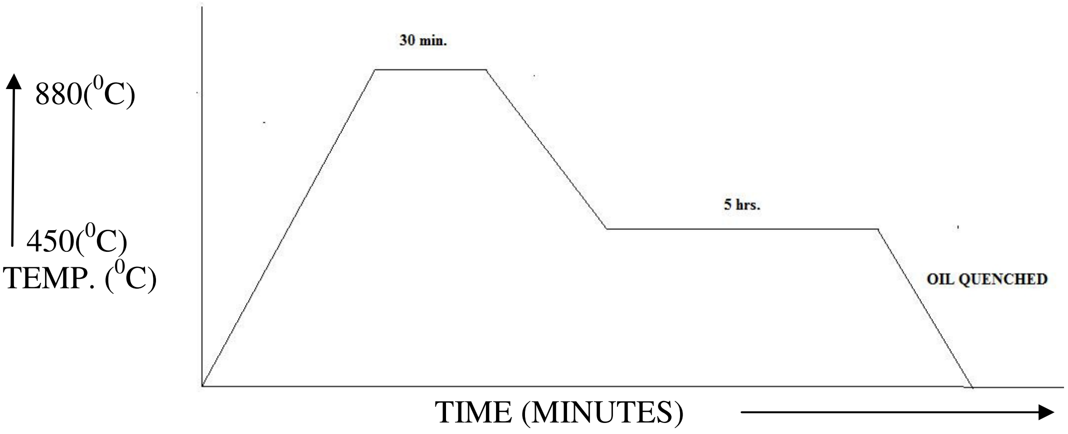


Fig.3: Heat treatment cycle 1

In cycle 2, the step bar of steps 14, 11, 6 and 3mm were austenitized at 880^{0}C for 30 minutes in a heating muffle furnace at a rate of 50-60^{0}C/hr. Then the furnace was cooled to 450^{0}C and soaked for 1 hour. After soaking, the samples were air cooled as depicted in Fig.4.

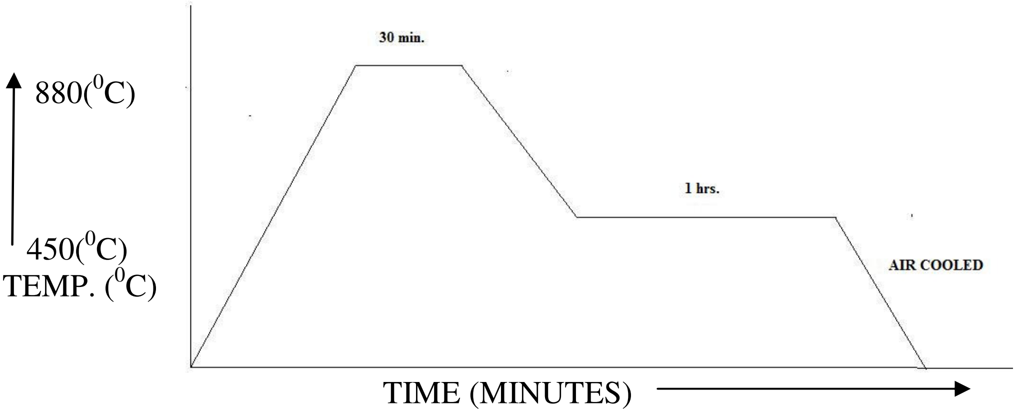


Fig.4: Heat treatment cycle 2

In cycle 3, the test samples of 2 and 3mm thin plates were austenitized at 900^{0}C for 30 min. in a heating muffle furnace. After austenitising, these test pieces were quenched in the salt bath (KNO_3 and $NaNO_2$ in the ratio 55 to 45 respectively) maintained at three constant austempering temperatures of 350^{0}C, 400^{0}C and 450^{0}C respectively. Isothermal transformation was allowed to continue for 5, 15, 30 and 60 min respectively at each temperature as shown in Fig 5.

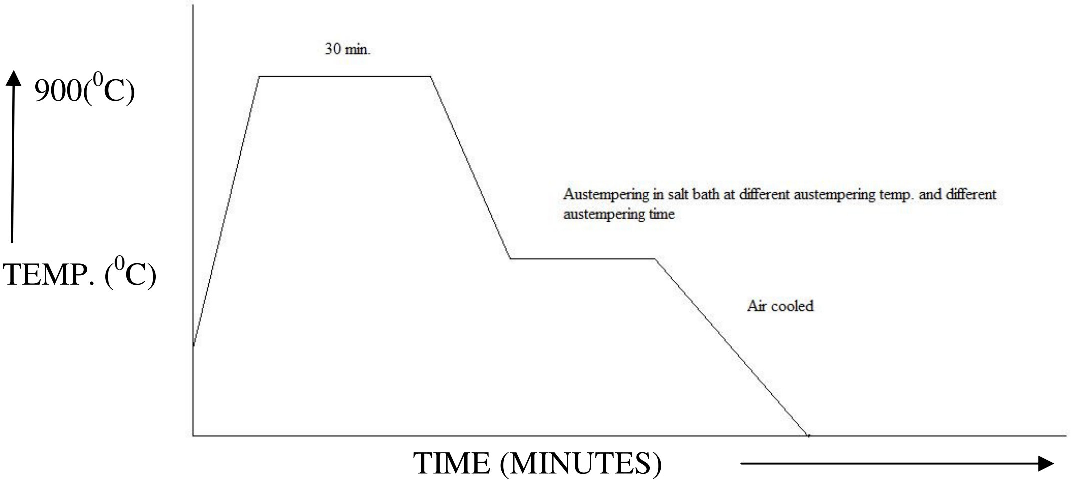


Fig.5: Heat treatment cycle 3

2.3 PROPERTIES EVALUATION:

The samples were prepared for optical and scanning electron microscopy after grinding, polishing and then etching with 2% natal solution. The hardness for each samples were taken on Brinell hardness testing machine of capacity 3000kg. At least three reading were taken on the sample of each heat and average of these three readings was taken as the hardness value of the as-cast as well as heat treated samples. Tensile test specimens were prepared from plate of 2 mm thickness as-cast and heat treated plates. For knowing the impact strength, specimens were prepared from as-cast and heat treated ductile iron plate.

3.0 RESULTS AND DISCUSSIONS

The cast plates and the step bars obtained from heat were analyzed in respect of casting quality, section thickness and heat treatment cycle on the structure and properties of ductile iron. These discussion and analysis were presented in four different sections.

3.1 Quality of casting,

3.2 Effect of Pouring Temperature and post inoculation

3.3 Effect of section thickness,

3.4 Heat treatment.

3.1 QUALITY OF CASTINGS

Plates and step bar were cast with riser and without riser. The model design (no riser), the metal flow and thermal behavior are shown in Fig6 (a)-(c) and casting in Fig.6(d).

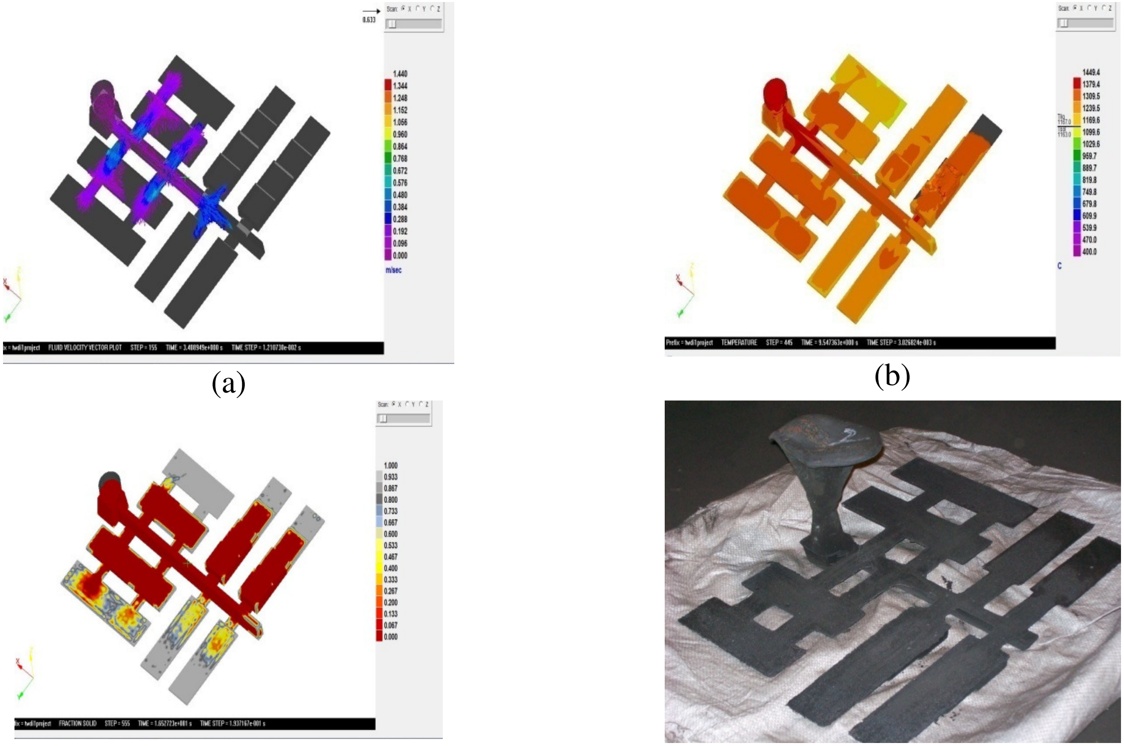

(a)
(b)
(c)
(d)

Fig.6:: (a) Fluid flow pattern, (b) Solidification pattern at initial stage
(c) Solidification pattern at advance stage, (d) Actual casting with gating system having no riser

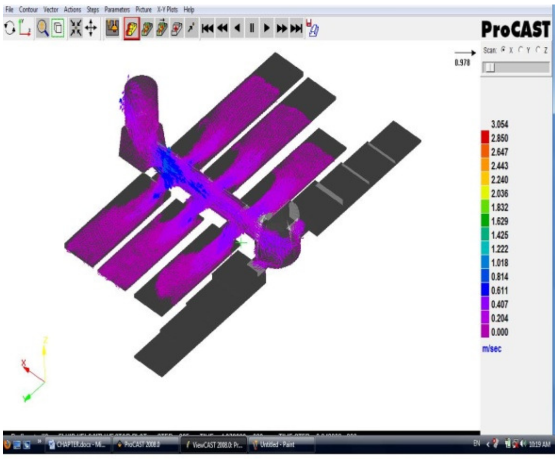
The 2 mm thin plate is attached with 3 mm plate by two gates near the sprue. The 5 mm plate and step bar are opposite to each other with runner. The fluid flow pattern observed as shown in Fig.6, depicts turbulence in 2 mm plate casting. The thermal behavior (Fig 6(c)) reveals the problem of cold shut in 3 mm plate casting which is attached with two ingates with a another 3 mm plate. However to check the simulation result similar moulds were made and the metal was poured. The defects like cold shut, shrinkage, misrun etc. occurred in some plate and step bar are shown in Fig.7.

(a) (b)

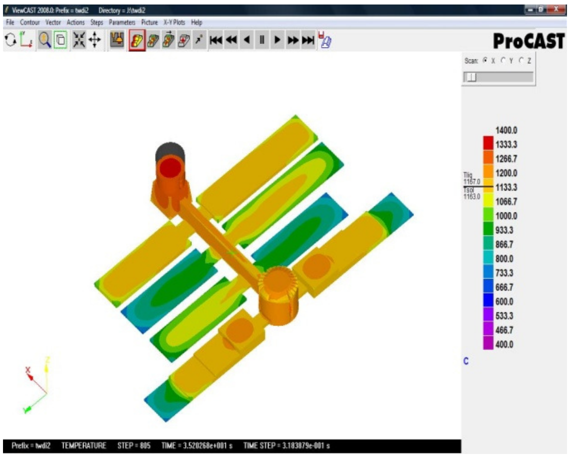
(c) (d)

Fig.7 : Casting defects (a) & (b) Cold shut in 3mm plates, (c) Misrun in 2 mm plate and (d) Shrinkage in step bars

In the production of thin wall ductile iron casting it is very important that casting should be free from shrinkage and other metallurgical defects. To achieve sound casting the model was modified and analyze by using simulation software “ProCAST”. Flow analysis and Thermal analysis was done and with these modified results, gating design was changed and a feeder was provided. The castings obtained with riser were sound and with good surface finish as shown in Fig 8 (a)-(d).

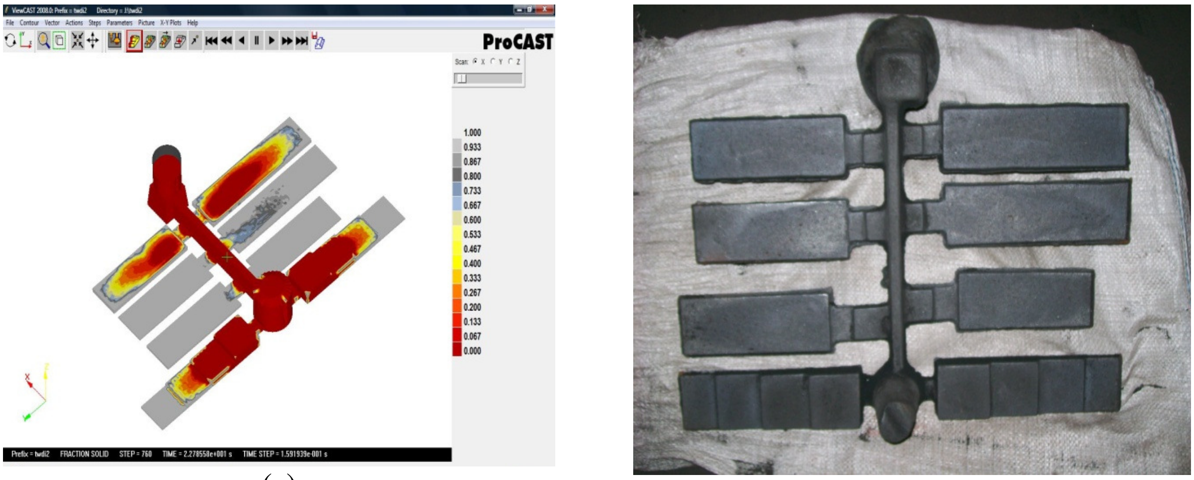


(a)



Prefix = twdi2 TEMPERATURE STEP = 805 TIME = 3.520268e+001 s TIME STEP = 3.183879e-001 s

(b)



(c) (d)

Fig.8: (a) Fluid flow pattern, (b) Solidification pattern at initial stage,

(c) Solidification pattern at advance stage, (d) Actual casting with gating system having riser.

3.2 Effect of Pouring temperature and post inoculation

The melt poured at three different pouring temperatures (1440^{0}C, 1400^{0}C, 1355^{0}C). For the 3 mm thickness plate, the increase in hardness observed with decrease in pouring temperature. This may be due to the faster cooling and low heat content which leads to fine nodular structure and also finer pearlitic structure. For a constant pouring temperature (1440^{0}C), the hardness decreases with increase in inoculants for a thicker plates (14mm). This may be due to the effect of faster cooling, low heat content and leads to fine nodule structure and also finer pearlitic structure. However for other thinner plates, the lower value of hardness observed for the plates inoculated at 0.35 wt % inoculants in comparison to the plates inoculated by 0.25 wt% & 0.30 wt% inoculants. The increase in fineness of nodules and correspondingly increase in ferrite phase is responsible for this change.

3.3 EFFECT OF SECTION THICKNESS:

The hardness data recorded of different section thickness of step bar and the average value is included in Table 2.To analyze the variation of hardness with section thickness, these hardness data were plotted and is shown in Fig.9. It may be observed from this plot that the hardness increases with decrease in section thickness.

The increase in hardness with decrease in section thickness may be related with the increase in the volume fraction of pearlitic phase due to faster cooling rate. This can be observed from the micrographs as shown in Fig.10. To analyze further the scanning micrographs were taken at nodule site and at matrix for 2 mm, 3 mm and 5 mm plates and are shown in Fig.11. It can be noted from these Fig. that the nodule size and pearlite lamellar spacing and thickness increases with increase in plate thickness. As increase in thickness of plate leads to slower cooling and results in increase in diffusion time of carbon atoms from the surrounding matrix to the nucleation sites of graphite nodule.

The slower cooling of thicker plates also causes slower transformation of austenite to pearlite and leads to coarser pearlitic structure.

Table 2: Effect of hardness with section thickness of step bar

Thickness (mm)	Hardness (BHN)
14	187
11	229
6	255
3	269

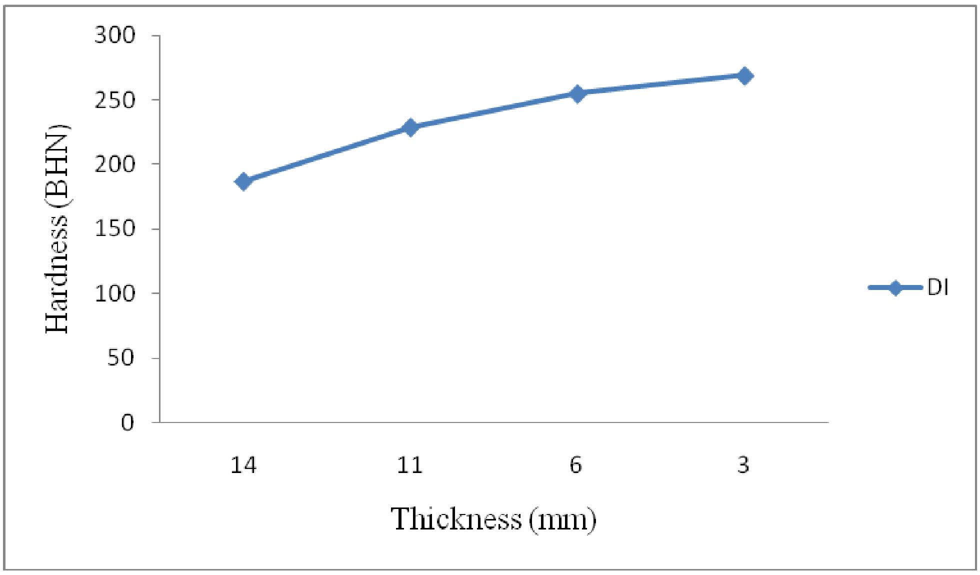
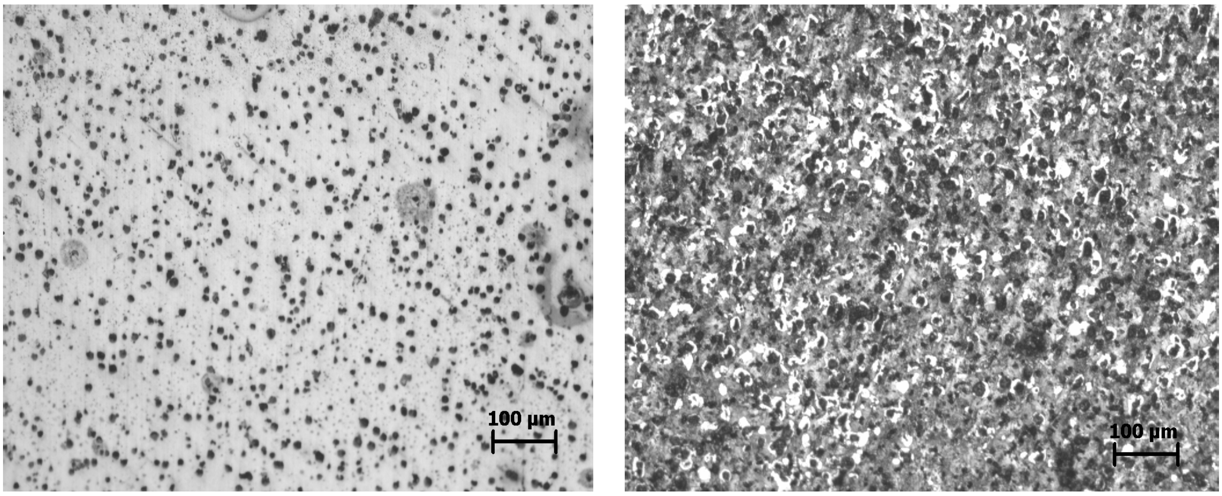
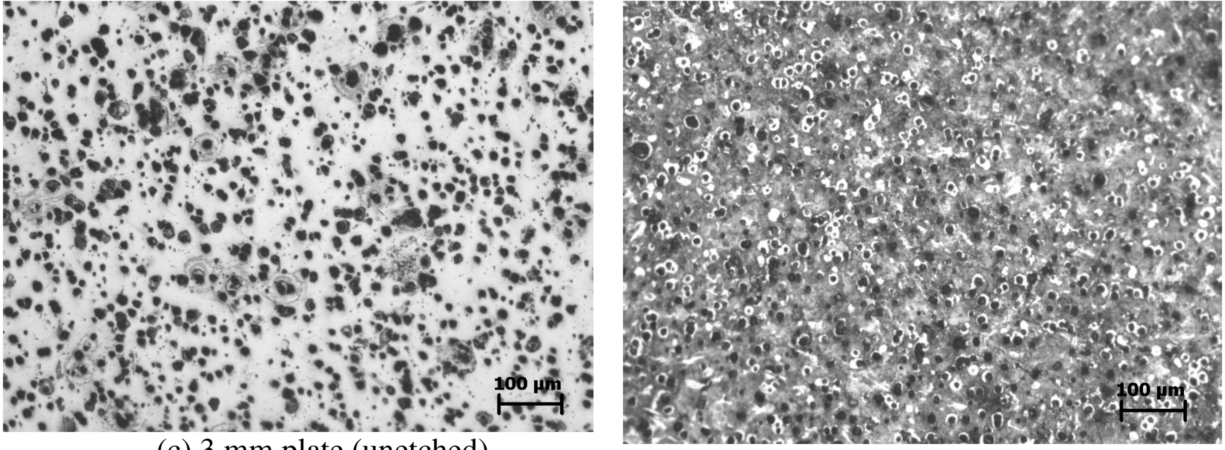


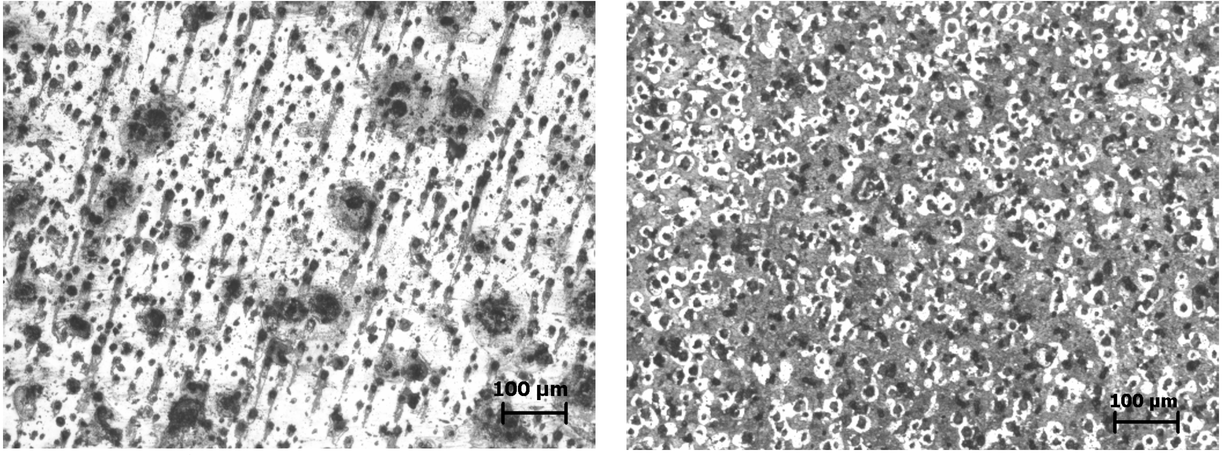
Fig.9: Variation of hardness with section thickness of step bar



(a) 2 mm plate(unetched) (b)2 mm plate (etched)

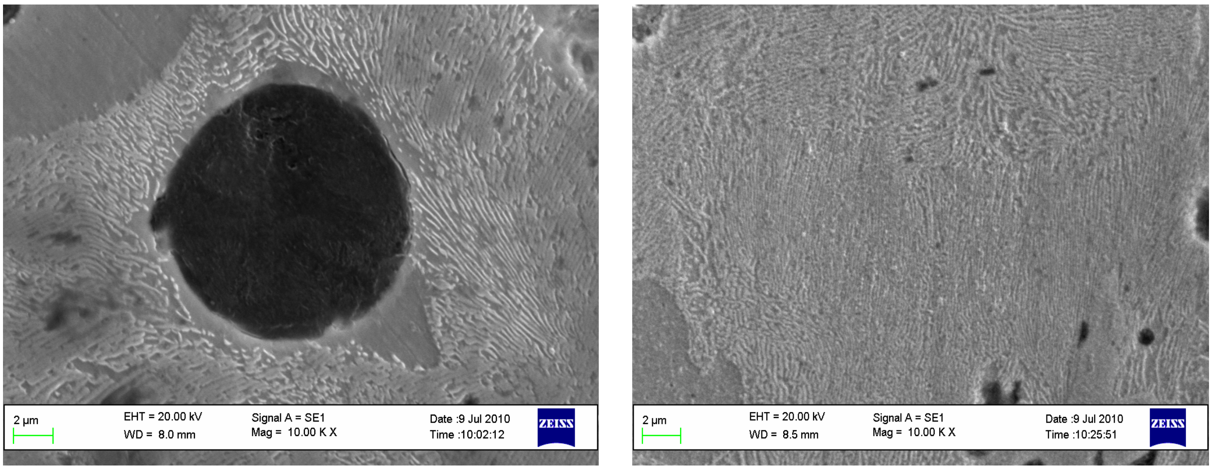


(c) 3 mm plate (unetched) (d) 3 mm plate (etched)

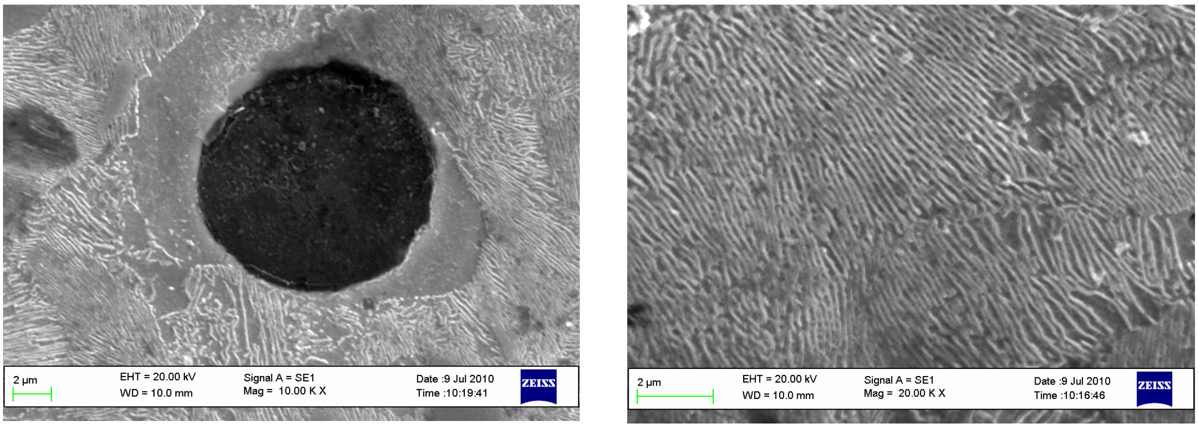


(e) 5 mm plate (unetched) (f) 5 mm plate (etched)

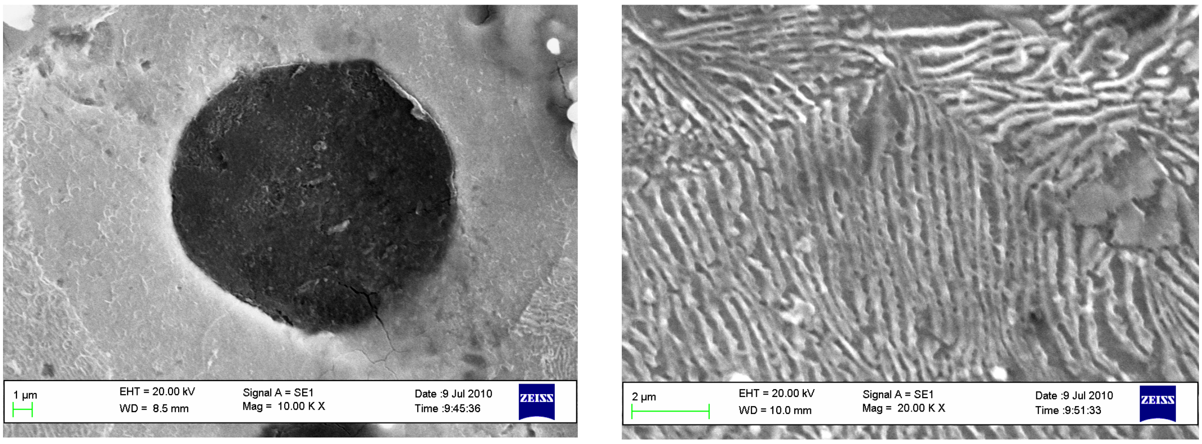
Fig.10: Microstructure of 2, 3 and 5 mm plates (as-cast ductile iron)



2 mm plate 2 mm plate



3mm plate 3mm plate



5mm plate 5mm plate

Fig 11: SEM image showing nodule size and pearlite matrix (as-cast ductile iron)

3.4 HEAT TREATMENT:

To relieve the internal stresses and improve the properties of ductile iron cast plates and bar, the heat treatment was carried out in three different cycles.

3.4.1 Heat Treatment Cycle 1 and Cycle 2 :.

The hardness data were recorded from the different section thickness of step bar and the average value is included in Table 2. The hardness for a constant section thickness remain more or less same after heat treatment in Cycle 1 and 2. To analyze the effect of heat treatment cycle on various section thickness of step bar, the data from Table 2 and 3 are plotted as shown in Fig. 12. It may be observed from Fig.12, a considerable decrease in hardness of annealed and oil quenched sample in respect of as-cast for all section thickness. It also shows the increases in hardness with decrease in section thickness for heat treated samples. To analyze the above variation, the microstructures were taken after heat treatment for one thinner plate (3mm) and another thicker plate (11mm) and the obtained microstructures are shown in Fig.13 (a)-(d). It may be noted from these microstructures that the thinner plate has comparatively lower volume fraction of ferrite and more pearlite than those of thicker plate.

During furnace cooling from 880^0C to 450^0C, the thicker plate has more heat content which may leads to more volume fraction of ferrite. However, all the plates tempered at 450^0C have relived internal stresses.

Table 3: Hardness with section thickness of step bars after heat treatment Cycle 1 & 2.

Thickness (mm)	Hardness (BHN)
14	156
11	163
6	170
3	170

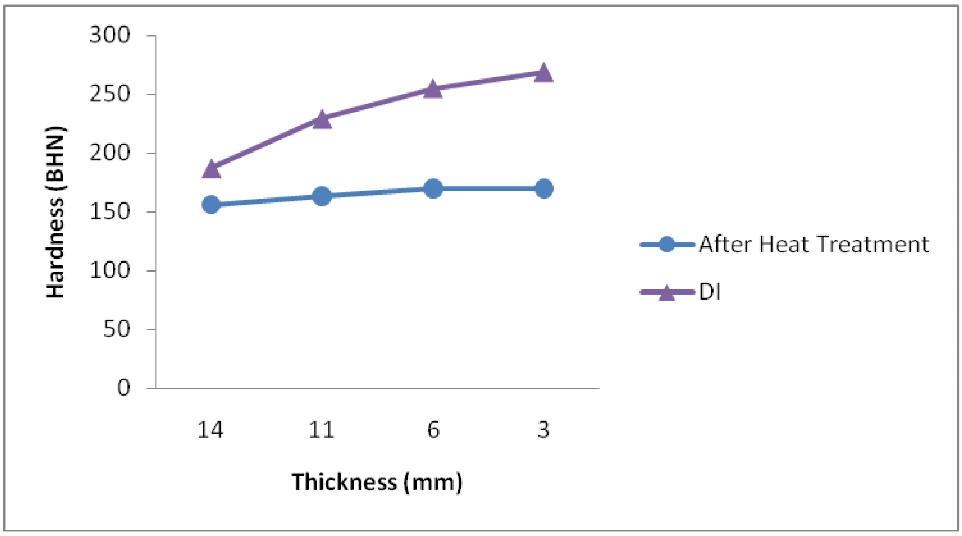


Fig.12: Effect of hardness with section thickness of step bar

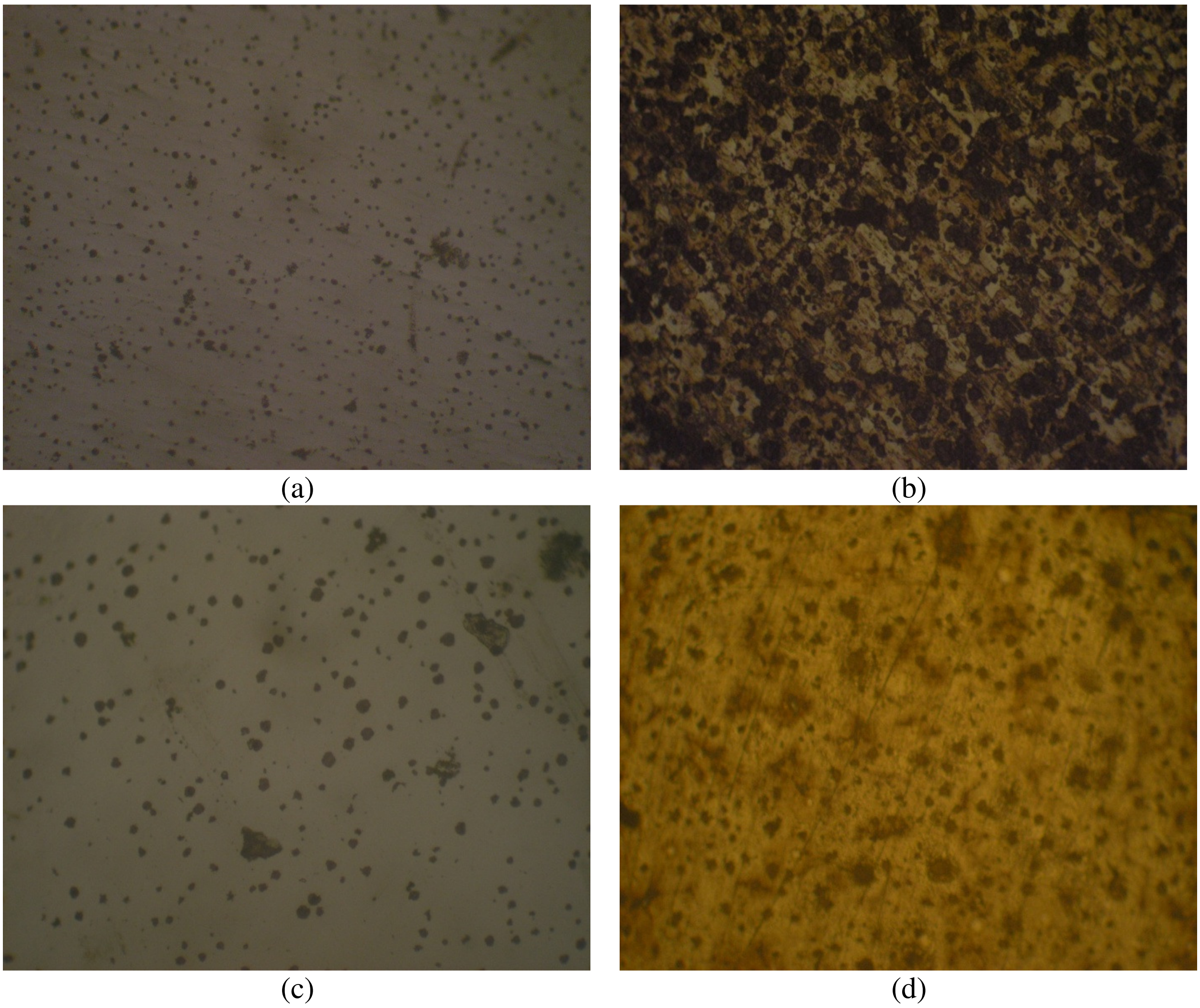

(a) (b) (c) (d)

Fig.13: Microstructure of plates of the DI after heat treatment (cycle 1) (a) 3 mm, unetched (b) 3 mm, etched (c) 11 mm unetched (d) 11 mm etched

3.4.2 Heat Treatment Cycle 3 (Austenitizing And Salt Bath Austempering):

To know the austempering behavior (effect of austempering temp. and time) on the structure and properties of above cast plates of 2 mm and 3 mm section thickness, the austempering cycle as discussed in section 2.2 is followed. The microstructure and hardness were taken for 2mm and 3mm thickness plates austempered at three different temperatures 350^0C, 400^0C and 450^0C and kept for four different holding time (5 min., 15 min., 30 min. and 60 min.) at each austempering temperature. The hardness value observed from the samples austempered at various temperature and time are recorded in Table 4.

The results obtained is presented and discussed in three different sections as effect of austempering time, austempering temperature and section thickness.

3.4.2.1 Effect of austempering time :

The above hardness data is plotted against austempering time for three different austempering temperature and is shown in Fig. 14 and Fig. 15 for 2 mm and 3 mm section thickness respectively. It may be noted from these plots that the hardness remain more or less same with slight variation with change in the austempering time at each austempering temperature. This is true for both 2 mm and 3 mm section thickness plates. By observing the microstructures in Fig.16 (a)-(d), it may be noted that the microstructures mainly consist of ausferrite and feathers of bainite with different volume fraction.

The observe slight difference in the volume fraction of bainite and ferrite leads to slight changes in hardness value of 2 mm thick plate. To further analyze, SEM photographs were taken for 2mm thickness plate austempered at 400^0C and for kept for 5 min. and 15 min., which are shown in Fig. 17 and 18 respectively. It can be found from these SEM micrographs (fig. 17) that the bainitic feathers are uniformly distributed at around nodules and in matrix. From comparing the Fig.17 and 18, the bainitic feathers look like same shape and size with small volume fraction of retained austenite, around it.

Table 4: Hardness Value of ADI Samples of 2 and 3 mm Plate

Sample No.	Austempering Temp.(^{0}C)	Austempering Time(min.)	Hardness (BHN) **2mm Plate**	Hardness (BHN) **3mm Plate**
Sample 1	350	5	288	269
Sample 2		15	292	272
Sample 3		30	298	278
Sample 4		60	285	255
Sample 5	400	5	321	269
Sample 6		15	325	275
Sample 7		30	285	285
Sample 8		60	255	272
Sample 9	450	5	285	255
Sample 10		15	272	249
Sample 11		30	292	275
Sample 12		60	298	255

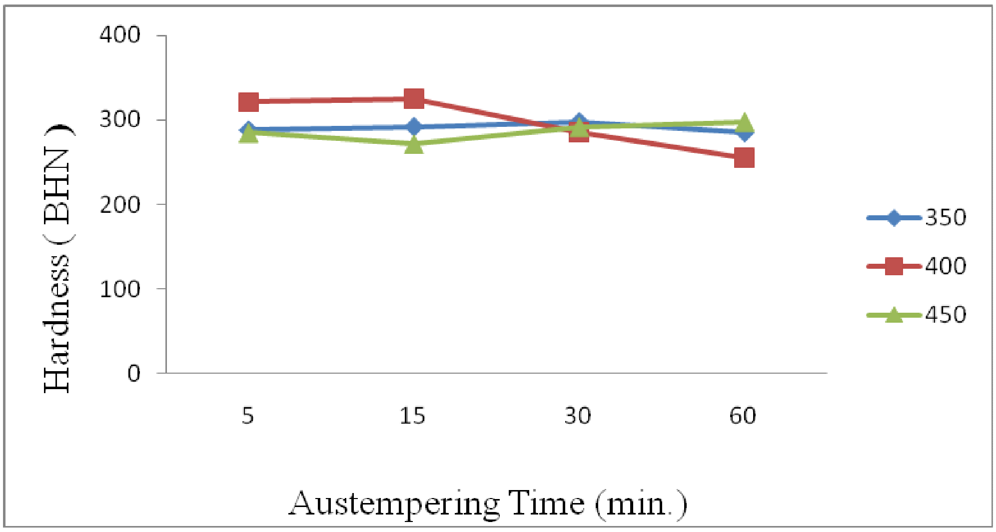


Fig.14: Effect of autempering time on hardness of 2mm plate

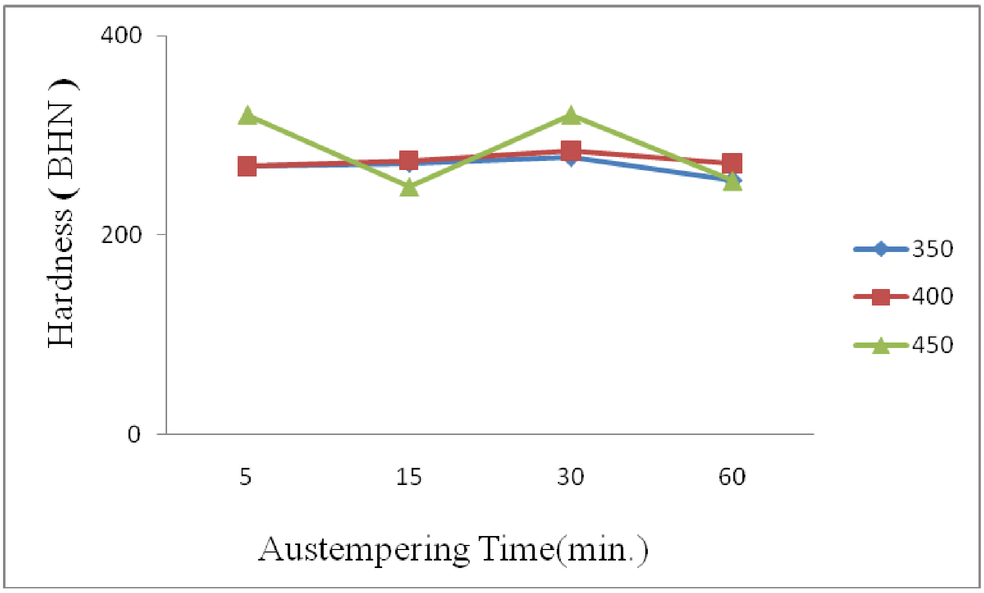
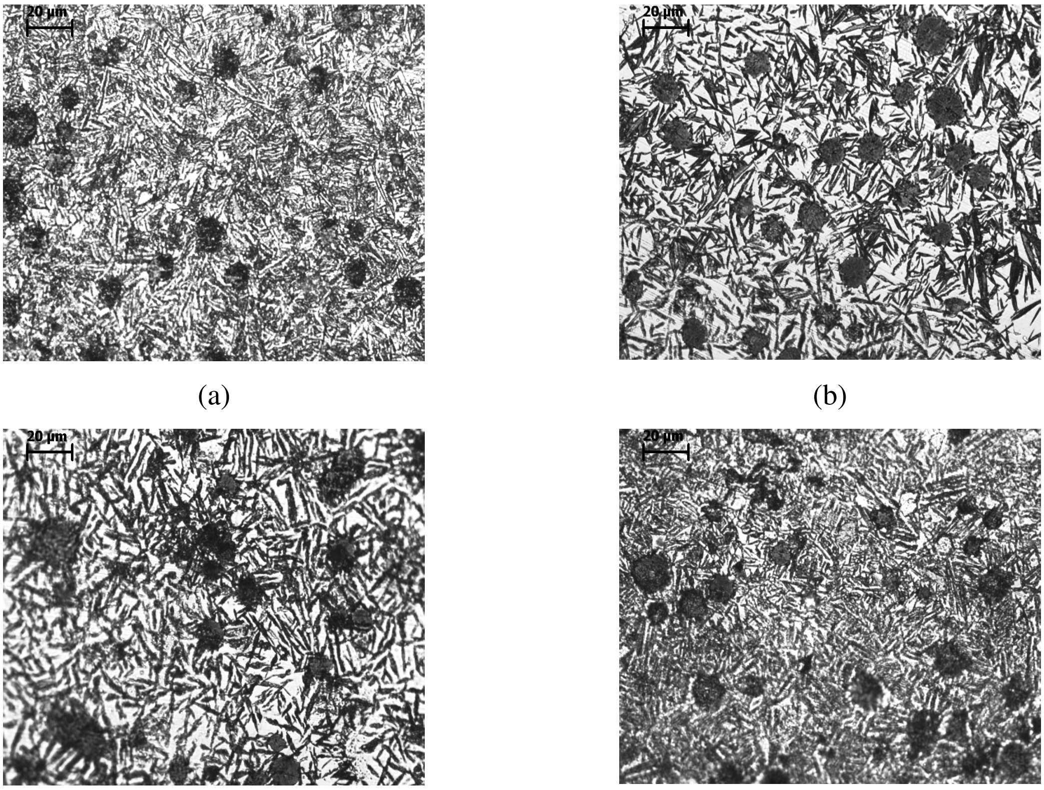


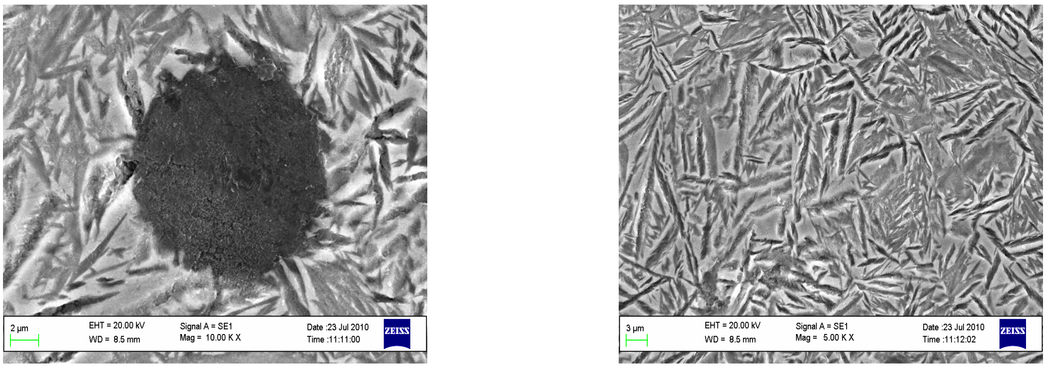
Fig.15: Effect of autempering time on hardness of 3mm plate



(a) (b)

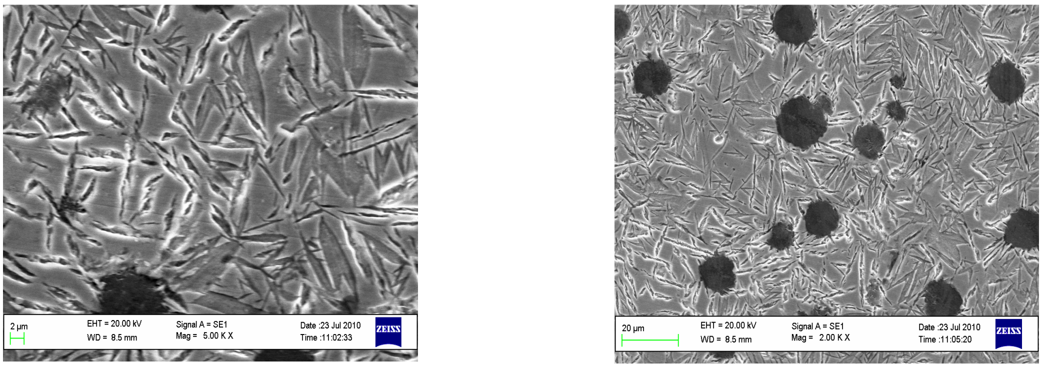
(c) (d)

Fig. 16: Microstructure of 2mm section thickness plate, austemperd at 400°C and kept for (a): 5 minutes, (b): 15 minutes, (c): 30 minutes and (d): 60 minutes,



(a) (b)

Fig. 17: SEM micrograph of the 2 mm thick plate austempered at 400°C and kept for 5 min.(a) at around nodule and (b) in matrix



(a) (b)

Fig. 18: SEM micrograph of the 2 mm thick plate austempered at 400°C and kept for 15 min.(a) at 5 KX and (b) 2 KX

To know the effect of austempering on the mechanical properties (tensile and impact), tensile test and impact test were performed on 3 mm thick plate as-cast and austempered at 400^0C for 15 minutes time. The stress-strain curve obtained is shown in Fig.19 and Fig.20. The obtained tensile properties data of as-cast and austempered DI for 3mm thick plate is included in Table 5. It may be noted from the Fig. 19 & 20 and also from Table 6 that the yield strength and UTS of ADI is around 600 MPa and 662 MPa respectively. However the same for as-cast is 460 MPa and 592 MPa respectively. The ADI also have lower ductility in comparison to as-cast plate (Table 6) The increase in both strength value and decrease in ductility of ADI in respect to as-cast DI plate may be attributed to the change in the structure from ferrite-pearlite to ausferrite-bainite (Fig.21 (a) & (b)). The observed values of impact for as-cast and ADI (2 mm thick plate) are shown in Table 6. It can be noted from this table that the ADI have lower impact strength in respect of as-cast. This may be due to the structural change of ADI as discussed above.

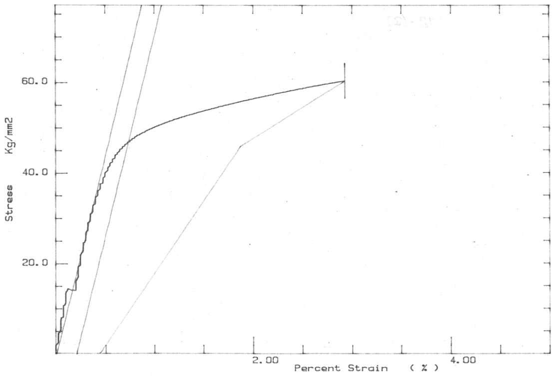


Fig.19: stress-strain graph for As-cast DI specimen (3 mm thick plate)

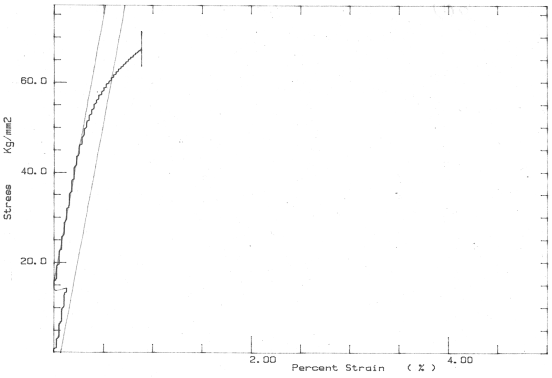
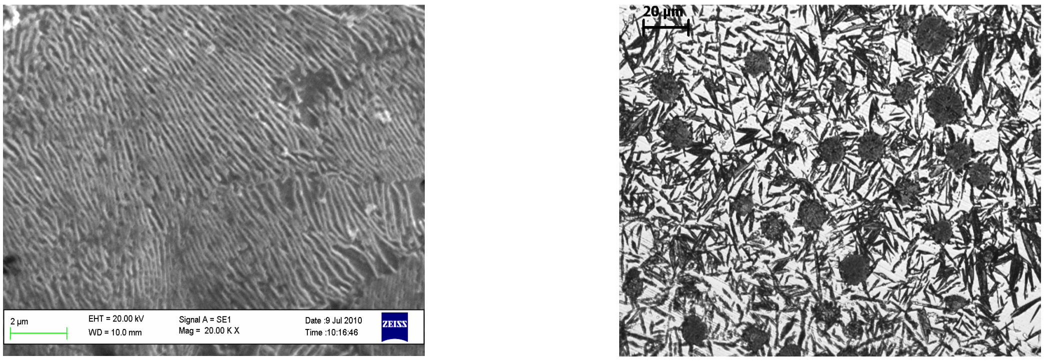


Fig.20: stress-strain graph for ADI specimen (3 mm thick plate),austempered at400^0C and kept for 15 minutes.

Table:5 Tensile properties data of as-cast and ADI

Tensile Test Specimen	Percentage Elongation (EL %)	Yield Strength (YS)		Ultimate Tensile Strength (UTS)	
		Kg	Kg/mm^2 (MPa)	Kg	Kg/mm^2 (MPa)
As-cast DI	2.93	2489	46.94 (460.48)	3200	60.35 (592.03)
ADI Specimen	0.88	3066	61.16 (599.97)	3382	67.45 (661.68)



(a) (b)

Fig. 21: (a) SEM micrograph of the 3 mm thick plate DI, (b) Microstructure of 3 mm section thickness plate, austemperd at 400°C and kept for 15 minute

Table: 6 Impact strength of 2mm As-cast and ADI Specimen

Impact Test Specimen	Impact Strength (Kg-m)
As-cast DI	0.12
ADI Specimen	0.08

3.4.2.2 Effect of austempering temperature:

To observe the effect of austempering temperature on ADI, samples were kept in salt bath at three different temperatures 350^{0}C, 400^{0}C and 450^{0}C for various holding time. The hardness data (Table 4) were plotted in respect of temperature and is shown in Fig. 22 and 23 for 2mm and 3mm thick plates respectively. It may be noted from these Fig. that the hardness value remain more or less same with respect to temperature for both 2 mm and 3 mm thick plates. However there is an increase in hardness at 400^{0}C for 5 min. and 15 min. holding time (Fig.22) for 2mm thick plate. It may be explained from observing the microstructures as shown in Fig.24 (a)-(c), it may be noted from these microstructures that at 400^0C, the structure is comparatively finer bainitic. The tensile and impact properties are also in agreement with this conclusion.

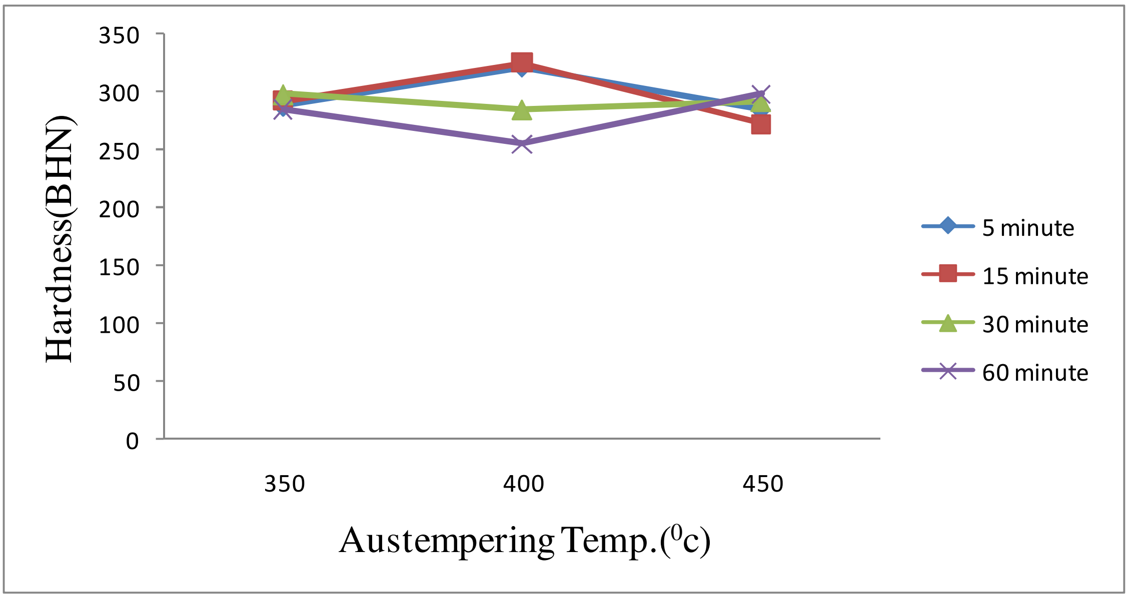


Fig.22: Effect of autempering temp. on hardness of 2mm plate

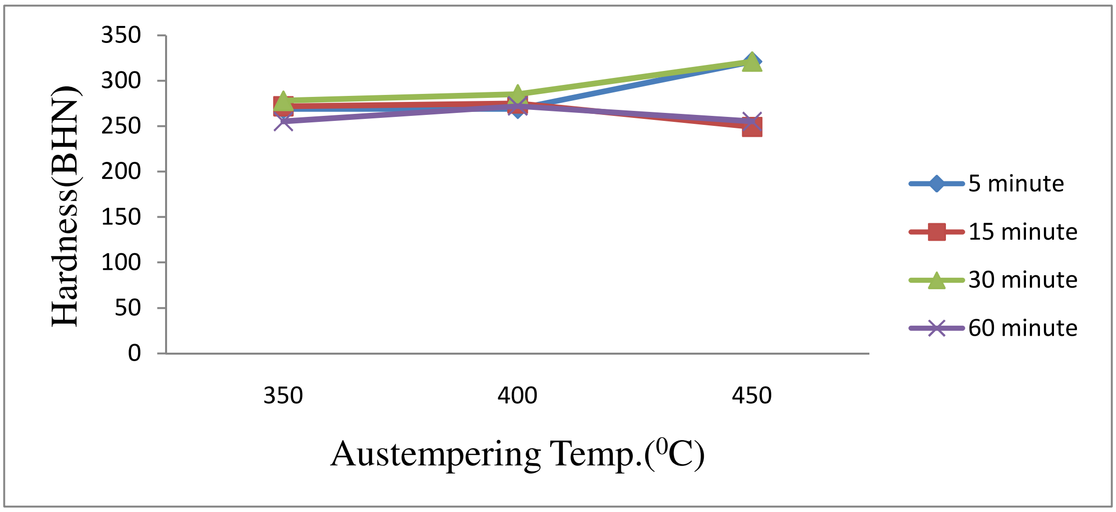
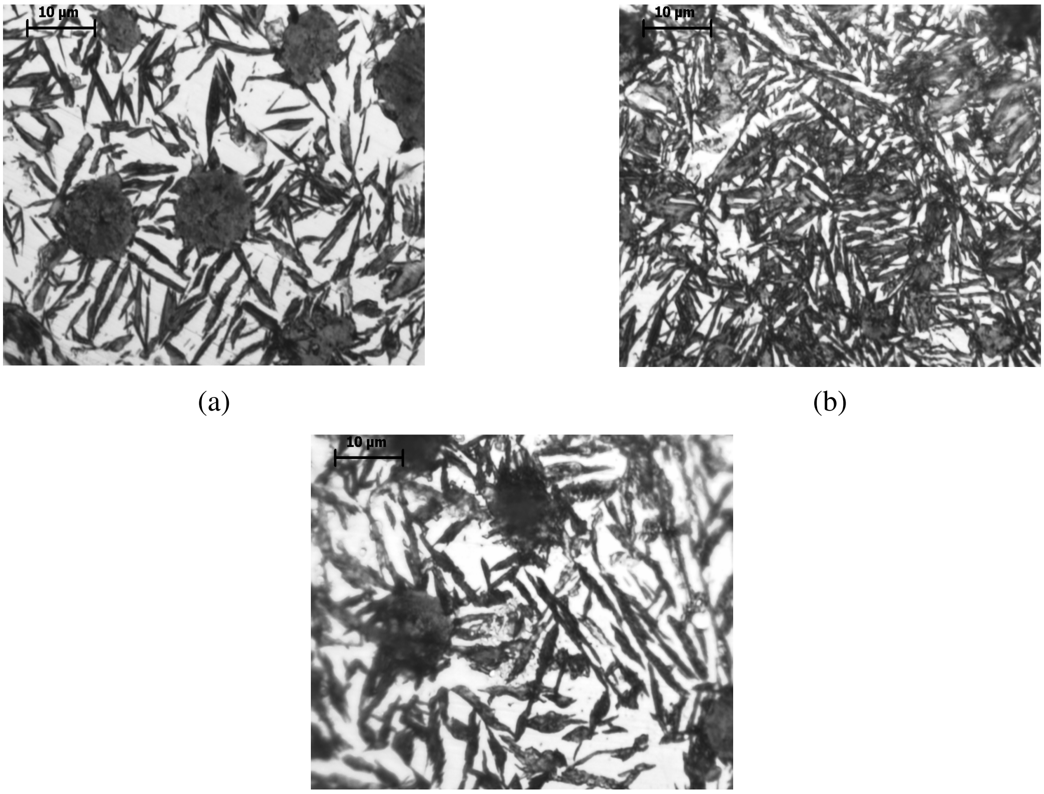


Fig.23: Effect of autempering temp. on hardness of 3mm plate



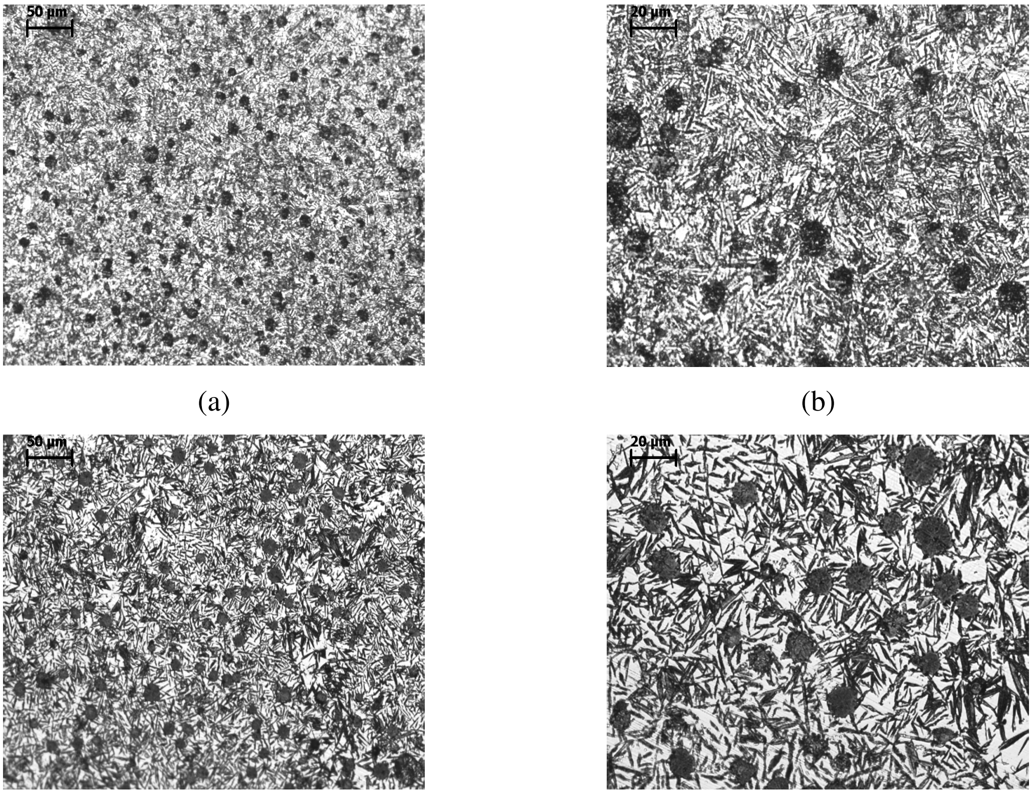
(a) (b)

(c)

Fig.24: Microstructure of 2 mm plate of ADI samples austempered at temp. (a) 350ºC (b) 400ºC (c) 450ºC at austempering time 5 minutes

3.4.2.3 Effect of section thickness:

To know the effect of section thickness on the structure properties of ADI, the two selective plates of 2 mm and 3 mm plates of DI were austempered at various temperature and time. It may be noted from the observed hardness data (Table 4) that the hardness of 3 mm plate is lower than the 2 mm plate for all different austempering temperature and time. This may be expected that the as-cast thinner plates have higher hardness in comparison to thicker plates (Fig. 4). To observe the microstructural change, microstructures were taken for 2 mm and 3 mm plates austempered at 400^0C and kept in salt bath for 5 minutes and are shown in Fig. 25 (a)-(d). These microstructures reveal that the thick plate (3 mm) has coarser and lower volume fraction of bainite in comparison to thinner plate (2 mm).



(a) (b)

(c) (d)

Fig. 25: Microstructure of the different ADI section thickness castings, austemperd at 400°C and kept for 5 min. (a) & (b) 2 mm thick plate and (c) & (d) 3 mm thick plate.

CONCLUSIONS

The following conclusions can be drawn from this study:

1. With suitable gating and feeding design, the thin wall ductile iron casting plates were obtained up to 2mm thickness.
2. For thicker plates is very negligible effect on the structure & properties by the variation of pouring temperature. However, for thin plate (3 mm) the hardness increase with decrease in pouring temperature due to increase in nodularity & finer pearlitic structure.
3. With increase in wt% inoculation, increase the volume fraction of ferrite in matrix & also leads to increase in nodule count which results in decrease in hardness.
4. With decrease in section of ductile iron plates, the hardness increases which may result due to increase in the volume fraction of pearlite with fine lamellar spacing.
5. The austenitizing followed by furnace cooling and then tempering at 450^0C leads to relieve in internal stresses and transformation to ferritic-pearlitic structure. There is negligible effect of cooling rate on the structure properties after tempering.
6. The austenizing followed by austempering of thinner plates at different temperatures and times leads to change in the structure ferritic-pearlitic to ausferrite-bainite.
7. The hardness remains more or less same with slight variation with change in the austempering time at each austempering temperatures. This shows that even 5 minutes austempering time is sufficient for transform the structures.
8. The yield strength and UTS of ADI are higher and ductility and impact strength are lower than that of as-cast DI plates. This may be attributed to the change in the structure change from ferrite-pearlite to austenite-bainite.
9. The hardness value remains more or less same with austempering temperature with slight increase in hardness at 400^0C for 5 min. and 15 min. holding time, for 2mm thick plate. This may result due to comparatively finer baintic structure.
10. The thicker plates which have been austempered at different temperature and times, has comparatively lower hardness than that of thinner plates. This may occurred due to coarser and lower volume fraction of bainite in thicker plate in respective thinner plate.

References:

1. Mortin Gagne, marie Pierre paguin and Pierre Marie, Dross in ductile iron: Source, formation and explanation, Foundry Trade Journal, November 2009,pp. 276-280.
2. J.M.Woolley, D.M.Stefanescu, Microshrinkage Propensity in Thin wall ductile iron casting, AFS Transaction 2005, pp. 637-643.
3. Dogan, K.K.Schrems, J.A.Hawk, Microstructure of Thin wall ductile iron casting, AFS Transaction 2003, pp.949-959.
4. L.P.Dix, R.Ruxanda, J.Torrance, M.Fukumato, Static mechanical properties of ferritic and pearlitic lightweight ductile iron castings, AFS Transaction 2003, pp.895-910.
5. P.David, J.Mossone, R.Boeri and J.Sikora, Gating system design to cast Thin wall ductile iron plates, Foundry trade journal, May 2009, pp.119-126.
6. C.F.Yeung, W.B.Lee, The morphology of solidification of thin section ductile iron castings, Elsevier Science Inc., 1998, pp201-208.
7. D.K.Banerjee and D.M.Stefanescu, Structure transitions and solidification kinetics of S.G cast iron during directional solidification experiments,AFS Trans.104,1991, pp747-759.
8. Karl. Martin Pedersen and Neils Tiedje, Nucleation and Solidification of Thin walled ductile iron- Experiments and Numericals simulation, Materials Science and Engineering A413-414 ,2005, pp358-362.
9. F.Mampaey, Z.A.Xu, Mould filling and solidification of a thin wall ductile iron casting. AFS Trans.1994, pp95-103.
10. F.Mampaey, Z.A.Xu, An Experimental and Simulation Study on mould Filling Coupled with Heat Transfer, AFS Trans. Vol 102 ,1994, pp96-179.
11. L.Nastac, D.M.Stefanescu, prediction of the gray to white Transition in cast iron through solidification modeling, AFS Trans.vol103,1995,pp329-337.
12. E.Fras, M.Gorny, Chilling tendency and nodule count in ductile cast iron , AFS Trans,2006, pp575-586.
13. T.Kanno, I.Kang, Effect of pouring temperature and composition on shrinkage cavity in speroidal graphite cast iron, AFS Trans. 2006, pp525-534.
14. http://www.predev.com/smg/parameters.htm
15. D. Venugopalan and A.Alagarsamy, Effect of alloy addition on the microstructure and mechanical properties of commercial ductile iron, AFS Trans. 1990, vol 98, pp395-400.
16. Foseco ferrous foundryman's handbook, Edited by John R. Brown, Butterwort Heinemann, Oxford, year-2000, pp.-78-79.

17. J. Achary, Tensile properties of austempered ductile iron under thermo mechanical treatment, Journal of materials engineering and performance, vol-9(1), year-2000, pp.-56-61
18. http://pubs.acs.org/doi/abs/10.1021/j100703a021
19. D. Krishnaraj and S. Seshan, Influence of austempering variables on the structure and properties of unalloyed ADI, AFS Transactions,vol-103,year-1995, pp.-767-775

20. G. Nadkarni, A.H. Behravesh, R. D. Warda, K.G. Davis and M. Sahoo, Low Carbon equivalent ADI , AFS Transactions, vol-103, year-1995, pp.-93-100

21. A. Refaey and N. Fatahalla , Effect of microstructure on properties of ADI and low alloyed ductile iron, Journal of materials science,vol-38,year-2003,pp.-351-362.
22. M. Gagne, C. Labrecque, M. Popescu and M. Sahoo, Effect of Silicon content and wall thickness on the properties of ADI, AFS Transactions,vol-114,year-2006,pp.-615-625
23. M. Nilli Ahmedabadi, B. Abassi Khazai and M. Bahmani , Effect of austempering variables on the mechanical properties of Ni-Mn-Cu ADI, AFS Transactions,vol-105, year- 1997, pp.-501-505
24. M.Heydarzadeh Sohi, M. Nilli Ahmedabadi, and A. Bahrami Vahdat, The role of austempering parameters on the structure and mechanical properties of heavy section adi, journal of material processing technology, year-2004, pp.-203-208
25. U. Batra, S. Ray and S. R. Prabhakar Tensile properties of copper alloyed ADI : Effect of Austempering parameter, asm international, journal of materials engineering and performance,vol-13,year-2004, pp.-537-541
26. Z.m.el-baradie, M.M. Ibrahim, I.A. El-Sisy and A.A. Abd El-Hakeem, Austempering of spheroidal graphite cast iron, material science,vol-40,year-2004,pp.-523-528
27. M. F. Hafiz, Impact properties and Fracture in Austempered S.G.–Cast Iron, AFS Transactions,vol-117, year-2009 , pp.-415-422
28. E . Fras, M . Gorny, and H.F. Lopez, Thin wall ductile iron and austempered ductile iron castings,AFS Transaction, year-2008, pp.-601-609,