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Effect of Gating Sprue Height on Mechanical Properties of Thin Wall Ductile Iron

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***Abstract*—**Effect of sprue/metal head height on mould filling, microstructure and mechanical properties of TWDI casting is studied. Results show that metal/sprue height of 50 mm is not sufficient to push the melt through the gating channel, but as it is increased from 100-350 mm, proper mould filling is achieved. However at higher heights between 200 mm and 350 mm, defects associated with incomplete solidification, carbide precipitation and turbulent flow are evident. This research shows that superior UTS, hardness, nodularity and nodule count are obtained at 100 mm sprue height.

***Keywords*—**Melt pressure and velocity, nodularity, nodule count, sprue height.

I. Introduction

DUCTILE iron thin section profiles (≤ 3mm) present danger of massive carbide precipitation in the as-cast sample [1], [2]. Precipitated carbide phase is brittle and negatively affects the mechanical properties of the iron matrix. Carbide precipitation in TWDI needs to be reduced or eliminated for improved strength, ductility and crack propagation resistance in automotive applications.

One crucial step towards the production of thin wall ductile iron (TWDI) castings that are defects free with the desired mechanical properties is ensuring that mould cavity is properly filled when molten metal is poured into it. Filling related defects include cold shut, mis-run, blow holes and sand inclusions. The goal of proper mould filling cannot be achieved without having proper gating system design and ensuring adequate melt fluidity. One of the critical element that has to be considered for producing a high quality sand casting product is the gating system design and risering system design [3], [4]. Improper design of gating and risering system results in cold shut and shrinkage porosities. These defects negatively affect mechanical properties. Therefore adequate care is necessary in designing gating and risering systems for improved yield of defect free castings [5]. Gating system components are choke diameter, sprue height, runner and in-gate dimensions. The desire to improve the mechanical properties of TWDI castings cannot be achieved if sound casting without defects is not achievable. There have been instances where melts with adequate fluidity have produced defective casting due to improper casting procedures or poor gating design. Reference [6] investigated the influence of gating system, sand grain size and mould coating on microstructure and mechanical properties of thin wall ductile iron. They studied the effects of the stepped and tapered runner designs and concluded that stepped runner gating system improves the graphite nodule characteristics, resulting in a positive influence on hardness and strength of TWDI casting. Reference [7] showed that the shape of pouring process and position of the ingates had an effect on the formation of oxide film in aluminum cylinder heads, based on the experimental observations; the author concluded that the main factor for smooth filling of the mould is the pouring process and the position of ingates. Also, the stream which is falling down from bigger distance has bigger kinetic energy and will cause larger turbulent movement as compared to the stream that is falling from smaller distance. The metallographic structure analysis confirmed that the structure from the sample poured at 15 cm has clearly more and bigger pores versus the structure from the sample poured at 1cm height. The gating design influences molten metal flow pattern which in turn affects temperature distribution/ heat transfer and modifies the progression of solidification. These processes affect final microstructure or phases formed after solidification of the as-cast thin wall ductile iron component. It has been shown that good gating system design could reduce the turbulence in the melt flow, minimize air entrapment, sand inclusion, oxide film and dross [8]–[13]. The formation of various casting defects could be directly related to fluid flow phenomena involved in the mould filling stage [8], [11]–[15]. For instance vigorous streams could cause mould erosion; highly turbulent flows could result in air and inclusion entrapments, and relatively slower filling may generate cold shuts [16]. Turbulent filling and flow in the gating system and mould cavity can increase mechanical and thermal attack on the mould [20]. Metal flow during mould filling is undoubtedly an important process in the casting industry. Mould filling is the first stage (from pouring to solidus temperature) of metal cooling [19].

Melt flow influences solidification time (t_s), which is an important parameter that could alter the microstructure and mechanical properties of the cast part. This parameter is influenced by design and dimension of gating components and also impart on the cooling rate of the casting.

Metal head height/pressure head/metal head is a vital gating component; it is the vertical distance between the metal pouring height and the top surface of the casting or simply the height of the metal in the sprue. This parameter directly

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influences metallo-static pressure as shown in equation 1. A higher metallo-static pressure gives higher velocity of molten metal resulting in higher fluidity. This is important to give the melt a longer flow distance. The head height should be sufficient to overcome the effects of surface tension, which inhibit filling of the mould cavity [18].

$$\text{Metallo-static Pressure } P_m = \rho g h \qquad (1)$$

where ρ is the metal density, h is the height of liquid metal column above the filling point and g is acceleration due to gravity.

The effects of casting design and head/sprue height on the quality of TWDI castings is studied in this paper in order to determine their effects on mould filling, microstructure and mechanical properties of TWDI castings.

II. Experimental Methodology

A. Effect of Casting/Feeding Design

The research samples patterns are 150 mm by 150 mm for three thickness (2, 3 and 4 mm), with two (2) patterns for each thickness. The dimension of the gating components and pattern plates are shown in Tables IA and IB respectively. Different feeding modes are designed namely: (1) Bottom Feeding (2) Top Feeding and (3) Side Feeding. Figs. 1-3 are the process assembly diagrams for the studied process.

TABLE IA
Dimension of Gating Components

Component	Bottom Feeding (mm)	Top Feeding (mm)	Side Feeding (mm)
Sprue (inlet/outlet diameter)	2mm- 14.74/11.22 3mm- 15.90/12.09 4mm- 16.73/12.72	2mm-12.40/9.44 3mm-13.40/10.1 4mm- 14.07/10.7	2mm-14.74/11.22 3mm-15.90/12.09 4mm-16.73/12.72
Runner	8.119 X 8.119	-	8.119 X 8.119
Ingates	2mm- 2 X 8.24 3mm- 3 X 5.49 4mm- 4 X 4.12	-	2mm- 2 X 8.24 3mm- 3 X 5.49 4mm- 4 X 4.12

TABLE IB
Dimension of Pattern Plates

Plate Thickness (mm)	Length (mm)	Width (mm)	Volume (mm3)	Mass (kg)
2	150	150	45,000	0.324
3	150	150	67,500	0.486
4	150	150	90,000	0.648

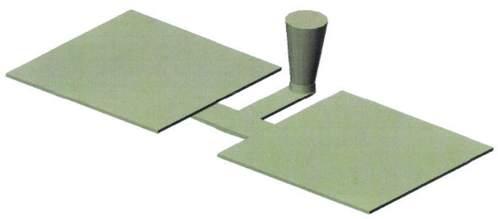


Fig. 1 Process assembly diagram for bottom feeding

In the bottom feeding the ingates are placed under the mould cavity so as to fill the mould by gravity and capillary action as in Fig. 1. For the top feeding mode the molten metal enters into the mould cavity directly from the top with no runners or ingates used as in Fig. 2. Lastly, in the side feeding the melt runs from the sprue to side gates through a runner as shown in Fig. 3.

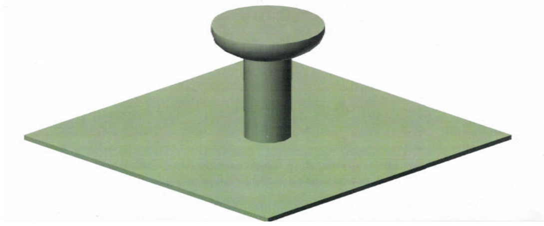


Fig. 2 Process assembly diagram for top feeding

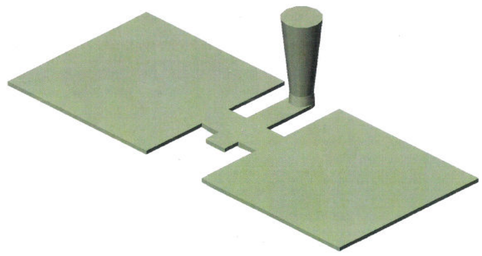


Fig. 3 Process assembly diagram for side feeding

The requirements of ASTM E2349 standard mould making procedures are employed using adequate moulding equipment to produce dense moulds. The moulding sand consisted of silica sand, bentonite, additives (coal dust and starch) and water. The dimensions of the drag and cope are 410 mm x375 mm with a height of 100 mm. The patterns for the cavity, runners and in-gates are placed in the drag section and rammed adequately while the sprue pattern is placed in the cope. A total of three moulds are prepared for each casting/feeding mode for the three thicknesses. Melting is carried out in a Dual Trak Induction furnace model VIP 1250-5R. The charge materials are mild steel scraps, ductile iron returns, ferrosilicon and graphite. Tapping is done after adequate carbon equivalent (CE) of 3.5-4.0 is reached in the molten metal at 1560^0C. Nodularizing treatment is performed by the sandwich method using ferrosilicon magnesium alloy granules covered with mild steel chips in a preheated treatment ladle. The ferrosilicon inoculants are added in the melt stream while transferring the molten metal from the treatment ladle to a preheated pouring ladle. Further inoculation is carried out while pouring into the moulds using powdered ferrosilicon in the stream by using a perforated pipe. The moulds and contents are allowed to cool for six hours after which the castings are shaken out. The chemical composition of the charge materials used is shown in Table II.

TABLE II
Chemical Composition of Charge Materials

Charge	wt. % (Kg)	% of Charge	C (Ch. Comp. %)	Si (Ch. Comp. %)	Mn (Ch. Comp. %)
Mild Steel	300	60	0.1	0.1	0.2
Ductile Iron Returns	170	34	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

Macro-examination of the as-cast samples is done to determine best casting design in terms of mould cavity filling, surface finish properties and surface defects. It is important to note here that the pressurized gating procedure is used to promote adequate fluidity of the melt with casting ratio of 3:2:1 which translate to sprue exit area: cross sectional area at runner: cross sectional area at in-gate.

B. Effect of Head/Sprue Height

The research samples patterns are same as above using dimension 150 mm by 150 mm for three thickness (2, 3 and 4 mm), with two (2) patterns for each thickness. Feeding of molten metal is done from top into a runner, which fills the mould cavity through two side ingates (Side Feeding). The process assembly of the gating design used is as shown in Fig. 3 as this design gave higher number of good castings from the previous part of research. The dimensions of gating components are shown in Table IA for the Side feeding design. The requirements of ASTM E2349 standard mould making procedures are employed using adequate moulding equipment to produce dense moulds. The moulding sand consisted of silica sand, bentonite, additives (coal dust and starch) and water. The dimension of the drag and cope is 410 mm x 375 mm with a height of 100 mm. The patterns for the cavity, runners and in-gates are placed in the drag section and rammed adequately while the sprue pattern is placed in the cope. A total of twenty one (21) moulds are prepared with seven sprue height for each thickness. Table III shows the sprue heights and sample designation used.

TABLE III
SPRUE HEIGHT AND SAMPLE DESIGNATION

S/No	1	2	3	4	5	6	7
Sprue Height (mm)	350	300	250	200	150	100	50
Sample Name	A1	A2	A3	A4	A5	A6	A7

TABLE IV
CHEMICAL COMPOSITION OF CHARGE MATERIALS

Charge	wt. % (Kg)	% of Charge	C (Ch. Comp %)	Si (Ch. Comp. %)	Mn (Ch. Comp. %)
Mild Steel	300	60	0.1	0.1	0.2
Ductile Iron Returns	170	34	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

Melting is carried out in a Dual Trak induction furnace model VIP 1250-5R. The charge materials are mild steel scraps, ductile iron returns, ferrosilicon and graphite. Chemical composition of charge materials is shown in Table IV. Tapping is done after adequate carbon equivalent (CE) of 3.5-4.0 is achieved in the molten metal at 1560^0C. Nodularizing treatment is performed by the sandwich method using ferrosilicon magnesium alloy granules covered with mild steel chips in a preheated treatment ladle. The ferrosilicon inoculants are added in the melt stream while transferring the molten metal from the treatment ladle to a preheated pouring ladle used for discharge of melt into moulds. Further inoculation is carried out while pouring into the moulds using powdered ferrosilicon in the stream by using a perforated pipe. The moulds and contents are allowed to cool for six hours after which the castings are shaken out.

C. Microstructural Analysis and Mechanical Testing

Macro-examination of the as-cast samples is done to determine surface and flow related defects such as cold shuts, incomplete filling, mis-run and blow holes. Brinell Hardness test is carried out using a 10/3000kg indentation ball on tester model Foundrax/B.H.D/1003402. Tensile property test is carried out on a test piece with dimensions as shown in Fig. 4, in accordance with ASTM E8 standard. Samples for microstructural analysis are cut, ground and polished according to standard procedure outlined in ASTM Standard E 3. 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 X100.

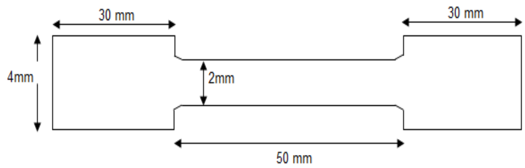


Fig. 4 Dimension for tensile test sample

III. RESULTS AND DISCUSSION

A. Effect of Casting/Feeding Design on TWDI

Observation by visual inspection revealed that the castings that are top fed, increased in thickness. This is attributed to the metallo-static pressure exerted during casting owing to gravity pull and turbulence at the entry point [13]. The pressures lift the cope and drag part of the mould up resulting in an expanded mould cavity and consequently increased thickness of the cast part. The castings obtained through bottom pouring/feeding are found defective due to incomplete mould filling. This is caused by inadequate pressure and velocity to push melt to fill mould cavity situated above in-gates. Thus, bottom feeding negatively affects mould fillability. The castings produced through side gate feeds are properly filled for the three thicknesses used except for some of the 2 mm thickness, for which some are not completely filled. The success here may be attributed to the absence of gravity and reduction in turbulence. Visual observation has shown that side feeding procedure produces the best results in terms of proper mould filling and surface finish, but the problem of incomplete filling of some 2 mm thick castings need to be addressed. There is the need to further improve on the molten metal fluidity and velocity to enhance mould filling and better surface finish. These could further improve both the physical and mechanical properties of the thin wall ductile iron castings. Thus, it is important to examine the effects of sprue/ molten metal height variation on mould filling ability and properties of the casting.

B. Effect of Molten Metal Height on Hardness of TWDI

The hardness of the samples shows a slight downward trend as the sprue height reduces (Fig. 5), except in the case of

50mm. The maximum hardness of 198, 193 and 215 HBN are obtained at 100 mm sprue height, with respect to 2, 3 and 4 mm thicknesses respectively. The low hardness values of 141, 124 and 129 BHN of 50mm height cast samples can be attributed to the problem of incomplete filling which is a melt flow related defect.

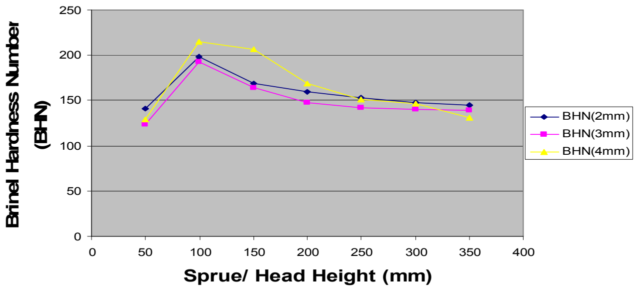


Fig. 5 Hardness responses of cast TWDI with sprue height

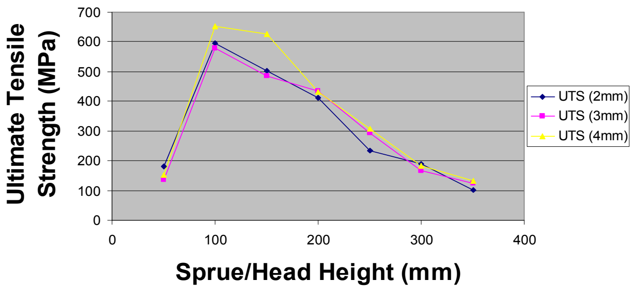


Fig. 6 Ultimate tensile strength of TWDI castings with sprue height

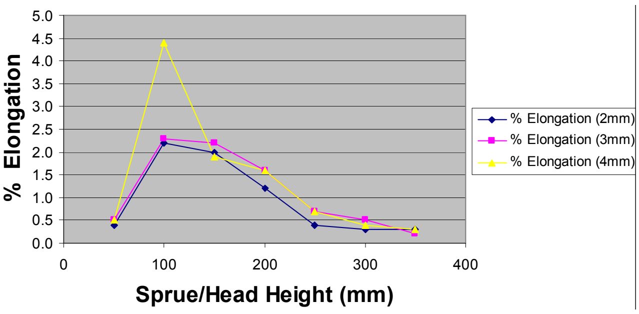


Fig. 7 Percent elongation of TWDI castings with sprue height

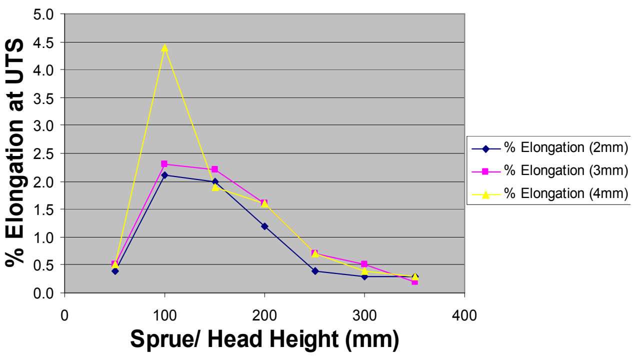


Fig. 8 Percent elongation at UTS of TWDI castings with sprue height

C. Effect of Molten Metal Height on Tensile Characteristics of TWDI

Figs. 6-8 are the ultimate tensile strength (UTS) and percent elongation responses of cast TWDI, except for the 50mm cast samples both UTS and percent elongation decrease as the sprue height increases. This suggests that the higher metallo-static pressure imposed on the molten metal from the longer sprue height is important to an extent. The castings from the 50 mm sprue height did not run due to insufficient head pressure to fill the mould cavity as fluidity and velocity is greatly impaired [17]. As the sprue height decreases from 350-100 mm the UTS increases progressively from 101- 596 MPa, 123-578 MPa and134-651 MPa for 2, 3, 4 mm cast thickness. The percent elongation similarly increases from 0.3-2.2, 0.2-2.3 and 0.3-4.4 for the 2, 3 and 4 mm cast thickness respectively. This suggests two problems; the first is the existence of turbulent flow and air entrapment associated with higher head pressure. Secondly, solidification related defects caused by heat transfer phenomena during its flow through longer distance due to increase in the sprue height of the gating channel [21]. These cause defects which are responsible for reduction in the mechanical properties of the TWDI castings as observed. Thus, it is recommended that sprue height should be kept as short as possible in the production of TWDI castings.

Table V shows that the head height has a significant effect on the heat transfer and solidification mechanism occurring in TWDI castings. This ultimately affects the tensile properties of the thin wall ductile iron castings. Sufficient head/ sprue height is necessary to properly fill mould cavity but exceeding this height becomes deleterious to the properties of the castings. Higher heights can lead to turbulent flow with flow related defects and significant temperature drop which is responsible for low UTS values. Table VI shows percent elongation trend with sprue heights of the TWDI castings.

TABLE V
UTS RESPONSES OF TWDI SAMPLES WITH SPRUE HEIGHT

Sprue Height(mm)		100	150	200	250	300	350
UTS MPa	2mm	596	503	411	233	190	101
	3mm	578	486	436	293	167	123
	4mm	651	627	432	309	183	134

TABLE VI
PERCENT ELONGATION WITH SPRUE HEIGHT

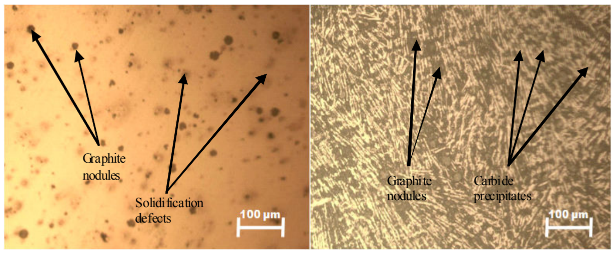
Sprue Height (mm)		100	150	200	250	300	350
% Elong.	2mm	2.2	2.0	1.2	0.4	0.3	0.3
	3mm	2.3	2.2	1.6	0.7	0.5	0.2
	4mm	4.4	1.9	1.6	0.7	0.4	0.3

D. Morphological Studies

The micrographs of samples A1 (2, 3 and 4 mm, Figs. 9-11) show poor nodule count and nodularity and presence of large proportion of carbide precipitates. The matrix of the unetched samples show features which are associated with sudden transformation arrest which are solidification defects. This is also observed for castings from the A2 range where the sprue height reduces to 300 mm. The unetched samples of A1 and

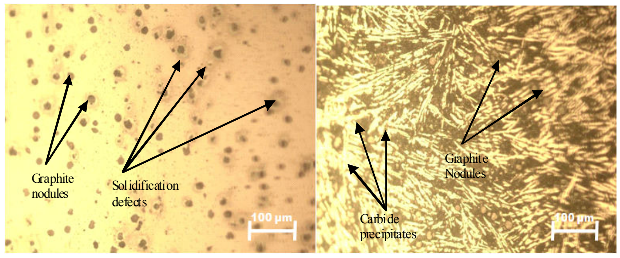
A2 range revealed some micro-voids and micro-porosity during macroscopic observations. These voids are also observed visually during the sample preparation for viewing. These micro-voids could be due to air entrapment [15] and insufficient graphitization since time is limited (faster cooling owing to longer sprue heights). Microscopic observation revealed solidification related defects as seen in most of the unetched micrographs poured from higher sprue heights, where transformation is stopped abruptly due to faster cooling due to temperature drop of molten metal. This is more evident in most of the 2mm plates [12]. This leads to the formation of a large proportion of carbide phase as seen in the etched micrographs of A1 and A2 (Figs. 12-14) range of samples. Significant temperature drop is observed as under-cooling occurred at the advancing melt front in the samples poured using longer sprue heights. This initiates early start of austenite transformation, resulting to insufficient time for the nucleation of the graphite phase. Cooling rate is fast in the thin plates as more heat is transferred owing to high cooling rate that leads to faster solidification rate through the austenite transformation region. It is recommended that the sprue height should not be too high, but should be high enough to achieve the required fluidity and velocity to push molten metal through to the cavity to be filled.

The above observed feature is replicated in A3 (Figs. 15-17) range of samples but with reduced intensity. In Figs. 15-17 of A3 samples for 2mm, 3mm and 4mm, the proportion of carbide precipitates is reduced, better nodularity and nodule count is observed. Features showing solidification defects in the matrix are reduced. The A4 (Figs. 18-20) range of samples shows better nodule count and nodularity with no primary carbides presence in the 4mm plate. However, a small proportion of solidification defects are noticed in the 2mm plates and increased significantly in the 3mm plate. Figs. 21-23 of the A5 range samples demonstrate good nodule count and nodularity, with the absence of the carbide precipitates. The microstructure here reveals the bull-eye ferrite phase around the graphite nodules embedded in the pearlite matrix. This structure yields better mechanical properties. Figs. 24-26 of A6 range samples poured at 100mm sprue height, possess the best microstructures in terms of nodule count, nodularity and matrix type. Typical bull's eye structure of graphite nodules surrounded by ferrite in a matrix of pearlite is evident in the A6 ranges. These microstructural properties explain the higher UTS, hardness and percent elongation values obtained with reduction in sprue height. Thus, this agrees with the previous recommendation that the sprue height should be kept as short as possible. However the micrographs of samples A7 (2, 3 and 4mm, Figs. 27-29) show poor nodularity and nodule count non-nodular graphite and large proportion of carbide precipitates in its structure. These poor mechanical properties can be attributed to incomplete filling.



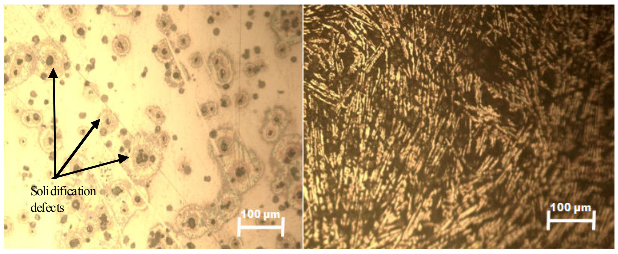
(a) (b)

Fig. 9 Micrograph of cast sample A1 with 2 mm thick section (a) unetched (b) etched



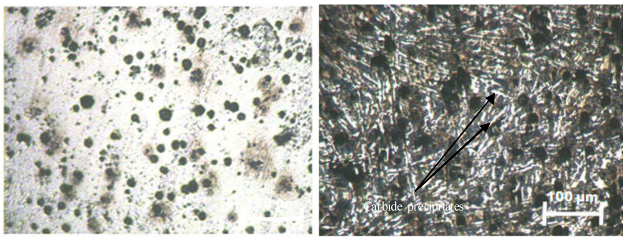
(a) (b)

Fig. 10 Micrograph cast sample A1 with 3 mm thick section (a) unetched (b) etched



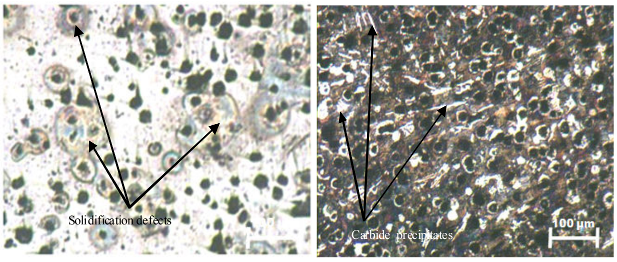
(a) (b)

Fig. 11 Micrograph cast sample A1 with 4 mm thick section (a) unetched (b) etched



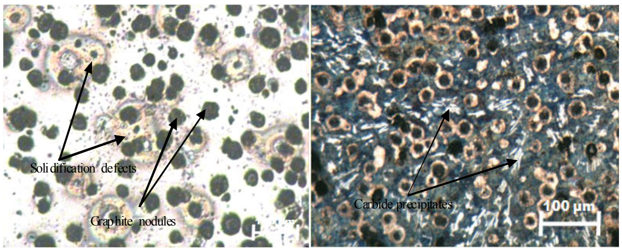
(a) (b)

Fig. 12 Micrograph cast sample A2 with 2 mm thick section (a) unetched (b) etched



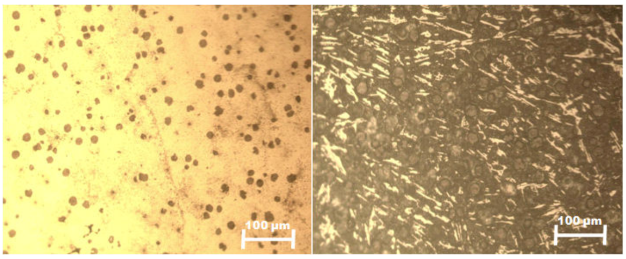
(a) (b)

Fig. 13 Micrograph cast sample A2 with 3 mm thick section (a) unetched (b) etched



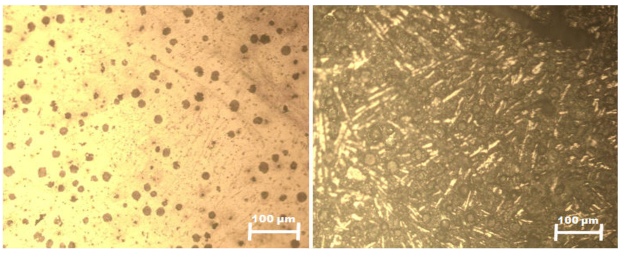
(a) (b)

Fig. 14 Micrograph cast sample A2 with 4 mm thick section (a) unetched (b) etched



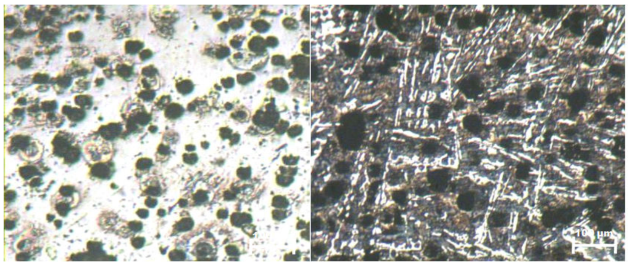
(a) (b)

Fig. 15 Micrograph cast sample A3 with 2 mm thick section (a) unetched (b) etched



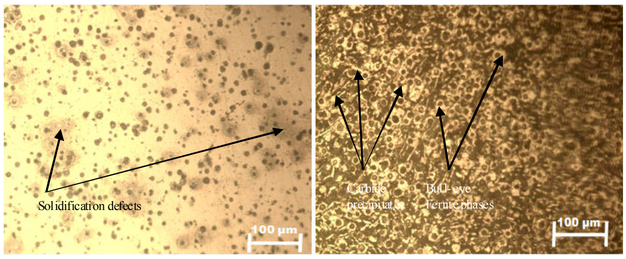
(a) (b)

Fig. 16 Micrograph cast sample A3 with 3 mm thick section (a) unetched (b) etched



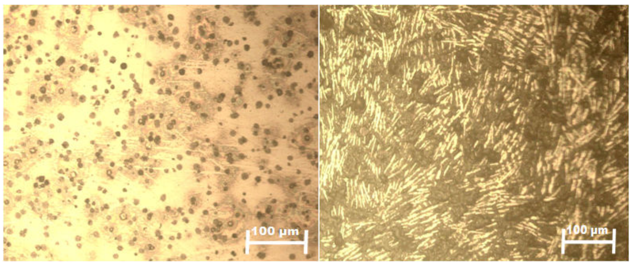
(a) (b)

Fig. 17 Micrograph cast sample A3 with 4 mm thick section (a) unetched (b) etched



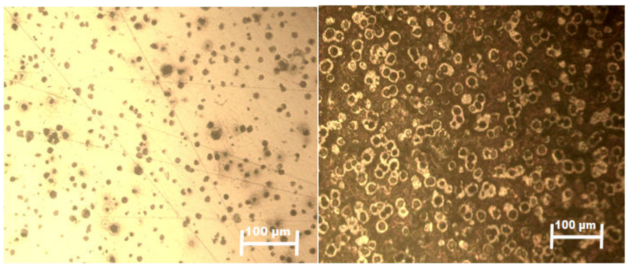
(a) (b)

Fig. 18 Micrograph cast sample A4 with 2 mm thick section (a) unetched (b) etched



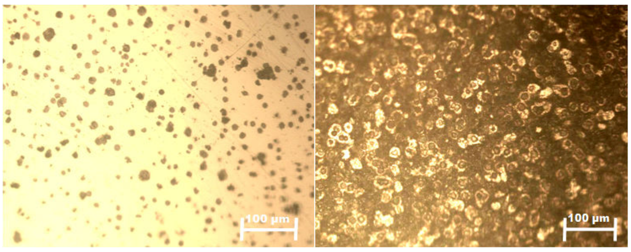
(a) (b)

Fig. 19 Micrograph cast sample A4 with 3 mm thick section (a) unetched (b) etched



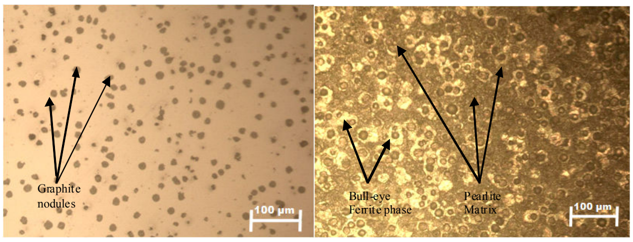
(a) (b)

Fig. 20 Micrograph cast sample A4 with 4 mm thick section (a) unetched (b) etched



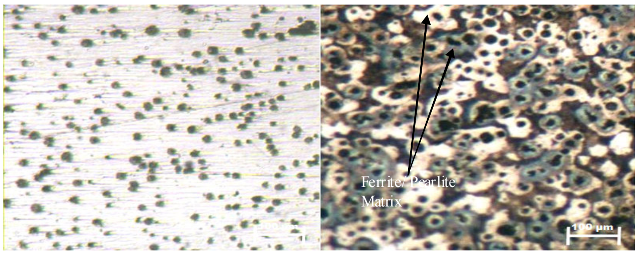
(a) (b)

Fig. 21 Micrograph cast sample A5 with 2 mm thick section (a) unetched (b) etched



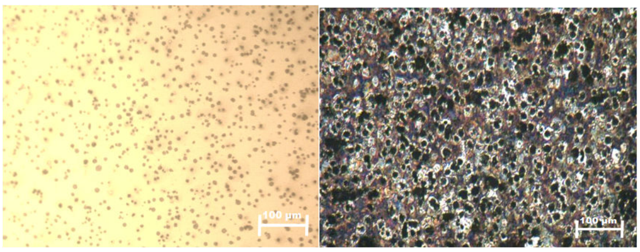
(a) (b)

Fig. 22 Micrograph cast sample A5 with 3 mm thick section (a) unetched (b) etched



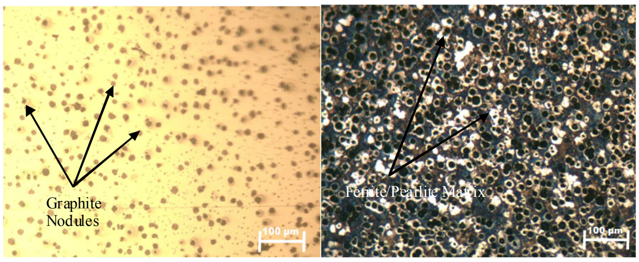
(a) (b)

Fig. 23 Micrograph cast sample A5 with 4 mm thick section (a) unetched (b) etched



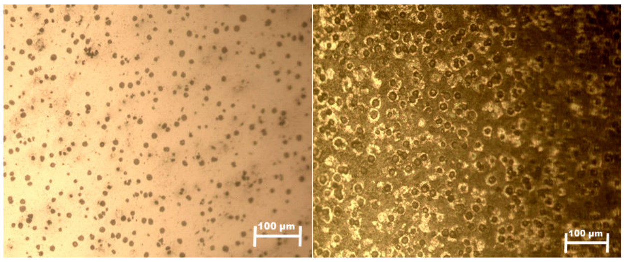
(a) (b)

Fig. 24 Micrograph cast sample A6 with 2 mm thick section (a) unetched (b) etched



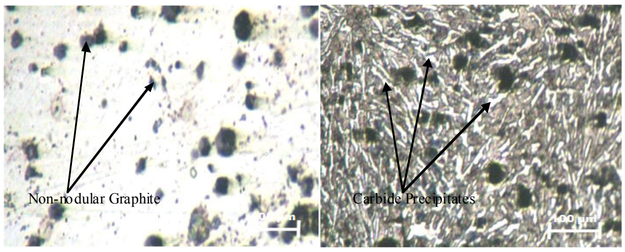
(a) (b)

Fig. 25 Micrograph cast sample A6 with 3 mm thick section (a) unetched (b) etched



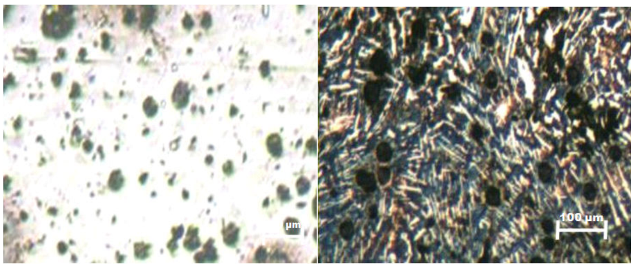
(a) (b)

Fig. 26 Micrograph cast sample A6 with 4 mm thick section (a) unetched (b) etched



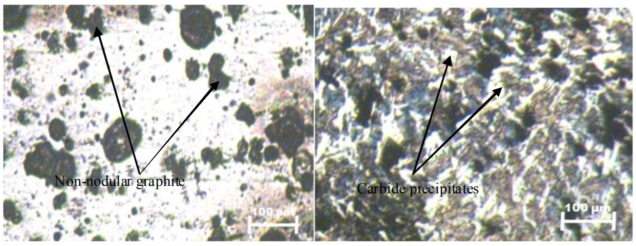
(a) (b)

Fig. 27 Micrograph cast sample A7 with 2 mm thick section (a) unetched (b) etched



(a) (b)

Fig. 28 Micrograph cast sample A7 with 3 mm thick section (a) unetched (b) etched



(a) (b)

Fig. 29 Micrograph cast sample A7 with 4 mm thick section (a) unetched (b) etched

IV. Conclusion

This work has shown that proper mould filling can be achieved by using side gating casting design. This would facilitate the production of defect free thin wall ductile iron castings. In this study, sprue/metal height is found to be an important gating system parameter to be considered during casting of TWDI. This parameter directly influences pressure and velocity of advancing metal front as it influences mould filling and affects the properties of the cast TWDI part. The sprue height of 50 mm is not sufficient to push melt through the gating channels effectively leading to poor run and incomplete filling of mould cavity whereas heights of 100 to 350 mm gave properly filled moulds. The 350 mm sprue height, however, yielded castings with inferior mechanical properties of 145,139 and 131HBN, 101, 123 and 134 MPa, 0.3, 0.2 and 0.3 % elongation for 2, 3 and 4 mm respectively. The 100 mm sprue height yields good mechanical properties of 198, 193 and 215HBN, 596, 578 and 651MPa, 2.2, 2.3 and 4.4 % elongation for 2, 3 and 4 mm respectively. UTS and BHN values were within the ASTM Spec. No. A536-80 with ferrite/pearlite matrix used for automotive components.

These suggest that metal head/sprue height is a vital gating system component to be considered in order to achieve proper mould filling and the desired mechanical properties of TWDI.

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