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SIMULATION BASED ANALYSIS OF SAND CASTING PROCESS PARAMETERS OF 46MnSi$_4$ ALLOY STEEL TRASH PLATE CASTINGS APPLICABLE FOR SUGAR FACTORY ROLLER STAND

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ABSTRACT

Quality of casting is affected by number of defects due to different causes including casting parameters.This paper focus on the analysis of sand casting parameters for casting trash plate applicable for roller stand used in sugar factories.The problems in casting the trash plate from steel of varius grades are porosity,sand sintering,shrinkage,miss run, cold shut and other related defects.In this particular research manganes steel 46MnSi$_4$ was used as a material for the production of the mentioned plate.Thus the objective of this study is to analyze the parameters affecting the quality of the the trash plate casting in order to establish standars that provide sound casting.To carry out the research mixied (experimental and therotical) methods that include physical observation, photographic analysis, intrview, testing and simulation methods were used. Purposive and convenience sampling technique were used for sample selection and sampling. Modeling of trash plate and gating system elements were first developed using CATIA software and simulation was carried out to show thermal history and solidification process of the plate using ANSYS software. The clay content and GFN of molding sand (silica) used were tested and result was found 6.983% and 49.805 respectively. The total solidification period of the trash plate was found as 769.05 seconds.

KEY WORDS: Casting parameter , solidification time, simulation, gating system design, casting defects.

INTRODUCTION

A casting is a shape[1] obtained by pouring liquid material into a mould or cavity and allowing it to freeze and thus to take the form of the mould. In sand casting process the mould is usually prepared from sands of various types as per the availability and quality requirements. As experience and literature[2] show castings may be damaged and rejected due to different defects including shrinkage,porosity,sand sintering and other related factors.The causes may be material composition,improper design of gating system, uncontrollable and non standard parametres and may be unskilled operators. Porosity is one of the main steel casting problem ,which occure during solidification of casting associated with incomplete gas evolution from the cast and the mold.The other major defect in sttel casting is shrinkage which also occur during solidification time and is the property of the sttel and thermal effect. As underlined in the works of [2,3],quality of casting products produced by sand casting process depends on the composition and condition of mold materials as well as process parameters. Mold materials condtion include moisture and clay content, grain fineness number of molding sand, amount of resin and catalyst and properties of sand like , permeability.Other factors may be initial (preheat) temperature of mold used, gating system, fluid flow.Process parameters affecting the soundness of the casting are mainly flow rate melt to fill mold cavity, metal fluidity, pouring time and speed, and temperature loss in the gating system. As defect of casting is raised from the melt material it self[3] metal chemical composition and its melting and pouring temperature are also considered as defect sources.Heat transfer condition of melt is also one factor that may cause various defects including shrinkage ,mis run,cold shut and porosity.In most cases casting defects result from improper pattern and gating system design, improper mould and core construction, improper melting and pouring practices[4]. In Literature [5] and from industrial practice it is known that development of defects like misrun, cold shuts, gas entrainment, mould erosion, hot tear and shrinkage porosity during mould filling process leads to poor part integrity and high casting rejection. A misrun defect occurs due to incomplete filling of mould cavity. A portion of the casting may be not filled, and necessary sharp corners may be rounded. A cold shut is visual and structural discontinuity formed where two or more metal streams meet below liquidus temperature of the cast metal. This can occur especially in large thin sections of the casting and is sucpitable for porosity source. As underlined in the work of [5] misrun and cold shut defects form when casting filling time is comparable with solidification time. These defects are attributed to casting design and pouring practice, and all casting methods (green sand, chemically bonded sand, permanent and semi-permanent mould) are susceptible. The casting filling system design in the foundry has long been based on the intuition and experience of the foundry engineers [5,6].

Author[7] used Ishikawa diagrams or fishbone diagrams to identify the reasons that affect the quality of sand castings and in the study almost all problems mentioned in the above paragraph contribute some part for on the defect formation and quality reduction. Simulation of solidification process[8] was performed that enables visualization of the progress of freezing inside a casting and identification of the last freezing regions that facilitated the optimized placement and design of feeders and feeding aids with improvement in yield while ensuring casting soundness without expensive and time consuming trial runs. The result presented shows that optimum location of riser using ANSYS software was used to helpe minimizing the solidification related defects, thereby providing a defect free casting. The optimal process parameter setting [8] significantly improved the mould yield, output ratio of metal, shorten manufacturing period, save energy and resource, reduce pollution, and improve the competitiveness of enterprises. Here, the effects of riser design, gating system, molding sand, oxidation and deformation of casting during heat treatment and machining allowance on the economical manufacture quality castings were reviewed. The studies presentd[9] that the quality of castings is affected by the technologies used in every production step such as pattern design, pattern plate utilization, feeding and gating system, sand technology, core design and its placement, melting and pouring, heat treatment and repair welding. The effects of slow and rapid pouring time [9] in casting practices have been studied and presented that slow pouring of metal leads to freeze fast before fill out the mould and would cause cold shuts in the castings where as rapid pouring of the mold cause erosion of the mold wall, rough surface and excessive shrinkage. The gating system [4,10] is the passage way in the mould for carrying molten metal to the mould cavity and thus designed to trap any dross or slag that may have come down the sprue with the metal. Pressurized gating system [11] restricts the rate of metal flow into the mould cavity and provides an opportunity for the slag to float at the top of the sprue or in the pouring basin and so stream velocities are highest at the gates just as the metal enters the casting. A typical gating ratio for most steel casting can be 4:3:2. The dimensions of the gating system [12] can be designed using laws of fluid dynamics namely, continuity law and Bernoulli's theorem. Riser that is a reservoir of molten metal and a decicive elment for sound asting [13], is used for shrinkage compensation especially in steel castings and designed based on its total volume, the number and location in relation to the casting, types, shapes and size, the need and use of chills, padding and riser treatments like exothermic and insulating materials. Solidification and cooling of castings process [14] depends on heat transfer from the part (metal) to the mould and from the mould to the environment through possible modes of heat transfer namely, conduction and convection.

From the above it is clear that various factors including casting parameters be the causes of defected castings that lead economic crisis for the industry and the particular nation.Various softwere analysis methods including simulation have been used to minimize defects in this regard.

MATERIALS AND METHODS

The trash plate material was $46MnSi_4$ alloy steel with the chemichal composition of **C**:0.459, **Mn**:1.15, **Si**:0.72, **S**:0.030, **P**:0.045 and other trace elements with the balance of iron. This trash plate is maily used for sugar industries applicable for roller stand that shrink the baggas of cane in order to separete jouce. Composition analysis of the mentioned steel was made using movable spectoro meter at one of the known metallurgical industry -ethiopia. The mold materials and additivies were also mixed silica sand (new and reclaimed silica sand), parting sand also fine silicas sand, resine (binders) and catalyst for activating the reaction of sand and riser (chemical), zirconium and

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dolomite powder (as facing sand also to mix with the sand to enhance refractoriness of the sand as well as to reduce the acidity of the silica sand), alcohol for drying, metallic paint for coding, deslaging agent while melting to form slag, pure aluminum for refining of the melt, asbestos (insulating material) for insulating the riser and its parts after pouring inorder to minimize heat lose from the riser.

METHODS

Method approach was experimental and theoretical (data analysis based on interview and physical observation). The research was carried out in one of the metal casting industry in Ethiopia where sand casting of ferrous metal is one of the key activity.Physical observation of the old trash plate damaged by defects were first observed and interviews and brain storming were made with the experts of the foundry factory to obtained the prilimenary information about aver all problems of the foundry factory and trash plate in particular. After observation and discussion a new trash plate was designed to be cast and before casting an experiment on the clay content and Grain Fineness Number (GFN) of the molding sand used to make the mold was carried out in the factory. One sample of trash plate with final dimensions (customer's specification) of 2300 mm length, 439 mm of width and 169mm of largest height cast from $46MnSi_4$ alloy steel was takne using purposive sampling method. Figure1 shows detail drawing of the trash plate taken as a sample. Design of the existing trash plate was modified and the pattern was prepared from wood that was coated with metallic paint.

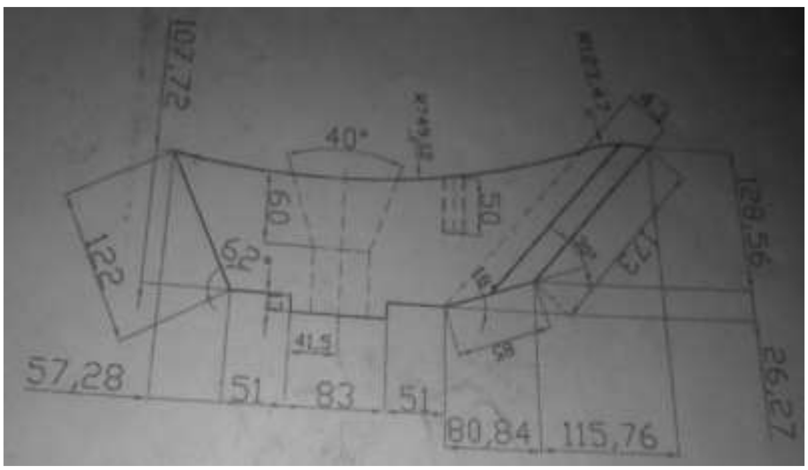

Fig. 1: Trash plate used as sample with specification limits

Four samples each weight 100grams. from mixed sand for GFN testing and also four samples each weight of 100grams. from new-sand for clay content testing were taken using convincens sampling method. The mold was prepared from dry silica sand that was furnished with dolomite powder bonded with resine. Sand was rammed on the pattern using hand molding tools. The mold cavities were painted with zirconium paste and heated using alcohol for drying. The chemical composition of alloying elements in trash plate casting was identified and anlyzed using mobile spectrometer,casting(melting) was carried out in corless induction furnace and pouring of the molten metal was performedusing teapot ladel. Simulation was carried out using ANSYS 14.0 software to show solidification process and thermal-history.

RESULTS AND DISCUSSION

The design specifications of trash plate ordered by customer was given as net weight of 684.41kg and final dimensions of 2300 x439x168mm in where, drawing was taken from data sheet of the industry. The plate pattern was developed from the given specifications using CATIA software taking in to account the machining allowance, shrinkage allowance and draft angle, which were given to it by foundry pattern section. The given allowances were 6mm, 2% and 1 degree respectively. Hence, its net weight, density, total volume and total surface area was determined and found 784.853kg, 7860Kg/m^3, 0.10m^3, 2.659m^2 respectively. As a result, actual sizes of the pattern of trash plate was length of base side of 2346mm and length of top side of 2350mm, width 465mm, largest height 176mm and largest thickness 121.26mm were found (Figure 2).

Befor molding was made analysis of clay content and grain fineness number (GFN) of the sand were carried out. The clay content of the new-silica sand used for mold preparation of trash plate casting process was determined taking four samples from the accumulated sand using Equation (1) **.**

$$\text{Clay content (\%)} = \frac{Wsb - Wsa}{Wsb} * 100\% \qquad [14] \qquad (1)$$

Where, W_{sb}-Weight of sand before washing, W_{sa}-Weight of sand after washing

Hence, the average clay content of the molding sand was calculated and average result was 6.983%. As per the test result, the clay content of the samples was compared to the standard clay content of ordinary silica sand grade A(5-10% of clay) and is with in the standard. As per literature[15], this sand has sintering (fusion) temperature resistance of up to 1350-1450^{O}C, which is less compared to pouring temperature of metal used (1650.6 ^{O}C). Since the mold cavity was coated with facing sand and refractory powder(dolomite powder) as well as painted with Zirconium then the pouring temperature of the metal did not affect the mold wall.It is also essential to mention the role of solidification process in heat and temperature lose dueto heat transfer that inturn protect the damge of mold wall by the pouring temperature. So, sand sintering problem on the cast was not observed. In addition, the sand with this clay content does not make the mold muddy and hence probability of porosity formation on the trash plate due to the clay content was less.

The Grain Fineness Number (GFN) of the mixed sand (new sand with prepared sand) wa sanalysed using the equation (2) [14].

$$GFN = \frac{\textit{Sum of all the products}}{\textit{Sum of percentages collected in each sieve}} = \frac{\sum M_i f_i}{\sum f_i} \qquad (2)$$

Where, Mi- multiplying factor (coefficient) for the ith sieve and fi- amount of sand retained on ith sieve

Based on the method above the GFN of mixed molding sand used in the foundryfactory of the particular industry was average GFN 49.805. So, the GFN value of the mixed sand used is fine grain sized sand compared to the standard GFN values of molding sands used in most foundry factories. Sand with such GFN values is highly compacted while mixed with resin and catalyst during mold making. Hence, a mold made from this sand was highly compacted and challenged gas bubbles to evolve and escape out from the mold cavity rather ramined in the liquid metal un dissolved,this consequently lead to porosity formation in the plate casting. The amount of risen and catalyst utilizated could also cause porosity formation in the trash plate casting. The high amount of risen used made the mold less permeable, less amount of resin resulted in reduction of mold strength. At the same time high amount of catalyst made the mold hard, which again reduced permeability and blocked the gas bubbles to escape from the mold and melt,while small amount of catalyst application lead to weak mold strength that consequently caused mold erosion and followed by sand sintering problem of the cast.Hence optimum amount of resin and catalysts was used on the process of mold making in the case.

As mentioned above from the designed values of pattern dimensions, the required mold made with sizes of length 2900mm, width 1000mm, total height of 610mm, choking range of 40mm. The initial temperature of the molds used was measured and was 27 ^{O}C, room temperature was taken as 20 ^{O}C and pouring was carried out at tilted angle of 7 ^{O}(from horizontal). External metallic chill with 46.5 x22x3 mm was constructed and used in the heavy section of the plates for directional solidification process. Figure 2 shows three dimensional model of the plate.

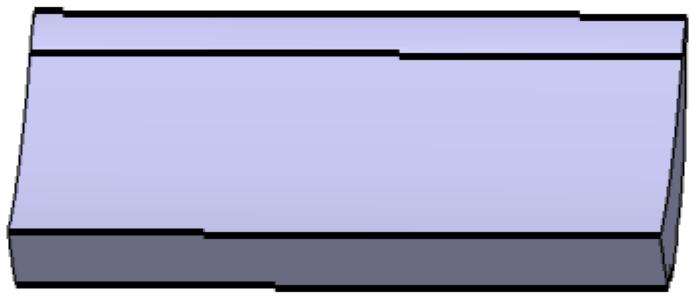

Fig. 2: 3D-Geometry of actual trash plate pattern

Gross weight was also determined in this particular wrok for the purpose of analyzing dimensional problems of gating system elements and associated parameters**.**The gross weight of casting can be defined as the weight of metal in mold cavity and weight of all gating system elements and yielding of material (excess weight of parts removed from casting by machining and grinding operations). As given by the foundry section, the maximum casting yield of steel material was 60%. Based on this the gross weight of casting, Wg, a single mold was determined using the following Equation [1].

$$\text{Gross weight of casting to poured} = \frac{\text{Net weight of trash plate casting}}{\text{maximum yield of steel casting}} \quad (3)$$

The required gross weight of metal obtained was 1308.1Kg. Compared to the standard design considerations this amount is small. This was due to the small sized pattern and molding flasks used. For the given shrinkage allowance considered and demand of client interms of total weight, which was 684.kg the pattern size was small to cast the required size and designed net weight of 784.853 Kg.

As pouring time was one of the essential casting parameters,it was vital to consider its effect in this particular process and hence**,** the pouring time was calculated by using the following Equation .

$$t_p = S(\sqrt[3]{TW_g}) \text{ (sec)} \quad [9] \quad (4)$$

Where, s-fluidity factor depending on iron composition and pouring temperature and given by the expert of 1.5,

T- thickness of casting wall and W_g-gross weight of castings (kg).

The calculated pouring time obtained was 82seconds which was sufficient to fill the cavity for the given plate.The obtained pouring time was also appropriate for for normal solidification process to take place in the mold.However other factors or parameters may affect the solidification process and thus further analysis was also carried out to identify the specific parameters that affect the quality of casting in this regard.

To determine the specific parameters affecting the quality of the plate cast, analysis was carried out on gating system design and associated elements.

The gating system used in casting of the trash plate was designed based on principles of pressurized type gating system. The critical gating system elements of the trash plate castings namely ingate, runner, sprue, sprue base, pouring basin, riser and riser base were designed. Here, total ingate areas required in one trash plate casting was calculated from the formula in Equation (5).

$$\sum A_i = \frac{W_g}{\mu \rho_m t_p \sqrt{2gH}} \quad [16] \quad (5)$$

Where, Ai-total ingate areas, Wg -gross weight of casting (Kg),ρ_m - density of metal used, H-effective height of metal head in the cope side of the mold which was 300mm**,** μ- efficiency factor or nozzle coefficient which is a function of gating system employed commonly used as 0.2**,** g - acceleration due to gravity**,** t_p - pouring time in seconds.

Thus, according to the equation used a single ingate area with a size of 52 $cm^2$was found. From this area volume and weight of molten metal accumulated in the ingate section was estimated by taking density of the material (steel) 7860Kg/m^3.The Volume and weight of metal found was 0.00026m^3 and 2.0436 Kg respectively.

The size of runner used was determined using gating ratio design rule [16] for steel castings. Tthe standard values used by the industry foundry department is 1:1.2:1.6 (ingate area: runner area: sprue exit area). So, area (size) of runner was estimated using Equation (6) as follow;

$(\mathbf{A}_{run})$ = ingate area(A_i) x1.2 (6)

From equation (6) above the maximum size of the runner was 62.4cm^2, that is uniform through out its length, and then the actual volume and weight of the molten metal accumulated in it were estimated and was also 0.00063m^3 and 4.952Kg respectively.

Similarly, the exit area (size) of the sprue, was determined using equation (6) in which the constant 1.2 is replaced by an other constant i.e 1.6, which was obtained from experimental analysis and the result was 83.2 cm^2. Hence, the exit diameter of sprue used was 10.29cm and its entrance diameter 11.8cm (area of 109.4cm^2, which was determined based on the factor (1.15) that multiplies the exit diameter **[12].** The minimum height of a sprue was considered and taken equivalent to height of the mold in the cope side (300mm). The actual sprue dimensions used were nearest to the designed values (top diameter 110mm exit diameter 80mm with fillet radius 2mm). As result, a sprue with 300mm height, entrance and exit areas 95 cm^2 and 50.27cm^2 respectively was found.

Since the supre used has frustum like shape, volume of the metal stored in it was calculated using the frustum formula of Equation (7) **.**

Volume of sprue (frustum shape) = $\frac{1}{12}\pi h\{d_{top}^2 + d_{exit}^2 + d_{top}d_{exit}\}$ [17] (7)

Thus, volume of the metal in the sprue was 0.002144137m^3. Therefore, weight of molten metal in the sprue was 16.852Kg.

Accordingly the obtained gating ratio in contras to the standard (2:3:4) for the case steel is smaller as a result of which the gating system elements used in trash plate casting were smaller which leads to turbulence flow of the melt.The turbulence flow has an effect of premature solidification of the cast and cause under fill of the cavity,which its consequence will be is under size of the plate and reduction of the over all weight.Early shrinkage was also expected as afactor of dimensional errors and porosity formation on the plate.

While pouring the melt to the gating system it is important to take the pouring speed of melt in to consideration. To do so the gap between the ladle lip and the pouring cup was measured and found 50cm .The measured value is pressure head and was the bottom optimum ladle level. The velocity of the molten metal at the pouring cup base was determined after falling a distance of 50cm plus the height of pouring cup with no coefficient of friction using equation (8)**:**

$V_p = \sqrt{2g\,h_p}$ [18] (8)

Where, Vp-pouring speed in m/se at a particular distance, g-acceleration due to gravity i.e., 9.81m/sec^2 and hp-pouring head in meter. Therefore, velocity of the metal at the pouring cup bottom and or sprue entranc was 3.63 m/sec. and the maximum critical velocity of the metal arrived at sprue bottom or exit was calculated using equation (9) by considered the surface friction coefficient (µ) of the sprue-wall .

$V_{max} = \mu\sqrt{2gh_s}$ [18] (9)

Where, V_{max}-pouring speed in m/se and h_s- sprue height in meter which was 300mm and µ-0.2. Therefore, the desired velocity at the sprue exit and entrance of the runner was 0.486m/se. Therefore, high pouring speed slowd downlow of molten metal that may be the cause for air entrainment and premature solidification ,which also may be the cause for the formation of misrun. In addition, high pouring head (preasure head) also creat higher flow velocity that causes mold erosion which in turn develop formation of poor surface roughness and sand sintering problem.In

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contrary smaller pouring head is responsible for turbulence flow of melt in the gating system. Turbulance flow is in its turn the reason for the formation of surface roughness.

The Reynold's number (Re) was also calculated todetrmine the fluid flow condition using equation (10) .

$$\mathrm{Re} = \frac{\rho VL}{\mu} = \frac{VL}{\upsilon} \quad [18] \qquad (10)$$

Where ρ - the fluid density, V - the velocity of the fluid at the sprue entrance and exit(estimated), L- important length dimension for the flow (for pipe flow, L is taken as the pipe diameter D_H or hydraulic diameter-which is sprue diameter). **μ** - the dynamic viscosity υ - the kinematic viscosity, where υ =μ/ρ.

Based on the above method the Reynold's number in sprue entrance and exit was 33,453 and 46,008 espectively. Reynolds number in the runner and ingate was calculated using equation (11), .

$$\mathrm{Re} = \frac{\rho V D_H}{\mu} = \frac{\rho V}{\mu}\frac{4A}{P} \quad [18] \qquad (11)$$

Where,D_H, equivalent hydraulic diameter ($D_H = \frac{4A}{P}$), and in this, A – Where,D_H, equivalent hydraulic diameter ($D_H = \frac{4A}{P}$), and in this, A – cross-sectional area and P-wetted perimeter (total perimeter of all channel walls that are in contact with the flow of each ingate element, i.e., Perimeters of runner and ingate were 29cm, and 34cm respectively). The equivalent hydraulic diameters of the runner and ingate were 6.21cm and 6.12cm respectively and the Reynold's numbers (Re) in the runner and ingate was calculated and the results were 35,902 and 33,965 respectively. Based on Re value (Table1) ,the flow was turbulence and that was one of the reason for the formation of porosity on the trash plate.

Table 1: Summery of metal flow and velocity results

Parameter	Locations					
	1	2	3	4	5	6
D_H -diameter-(m)	0.110	0.08	0.0621	0.0621	0.0612	0.0612
Area (m^2)	0.0095033	0.0050266	0.0045	0.0045	0.0052	0.0052
Velocity(m/sec)	0.257	0.486	0.543	0.543	0.469	0.469
Flow rate(m^3/se)	0.002443	0.002443	0.002443	0.002443	0.002443	0.002443
Re	33,453	46,008	35,902	35,902	33,965	33,965

One of the important gating system element is the riser.This element is the determinant elment on the soundness of casting. The riser used in the trash plate casting was considered to be large enough to satisfy requirement of the designed plate. For soundness of trash plate casting the solidification time of the metal in the riser was taken as 1.5 times the solidification time of the casting in the mold and can be calculated based on equation (12) ,

$$t_r = 1.5\, t_C \quad [1] \qquad (12)$$

By substituting t_r with Cs(r){Mr}^{2} and t_C with Cs(c){Mc}^{2} in to equation (12) for side mounted riser, the top and exit diameters of the riser were related in equation(13).

$$\left(\frac{V}{A}\right)r = 1.22 \left(\frac{V}{A}\right) c \qquad (13)$$

Since, the shape of the riser is frustumed cylindrical, the volume to surface area ratio was analysed using equation{(14),

$$\frac{V}{A} = \frac{\frac{\pi h_r}{12}(dt^2 + de^2 + d_t d_e)}{A_l + A_t + A_e} \quad [17] \qquad (14)$$

Where, A, A_L, At and Ae- total surface area, latent area, top cross-sectional area and exit cross sectional area of the riser respectively also L-latent length of riser.

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Based on the equations (13),(14) the dimensions of the riser were dt= 0.244m or 244mm and possible maximum height of the riser, h= 1.5*d = 366mm.

The top diameter of the riser was determined by taking 1.15 times the exit diameter.It was done to avoid air aspiration that can be induced in the wall of the riser cavity during metal pouring, and was 213mm. Hence, a pattern (near to the estimated values) with sizes of 250mm, 230mm and 365mm as top diameter(dt),exit diameter (de) and height respectively was selected to make trash plate cavity.

Therefore, total volume of metal that reserved in the riser was analyzed on the basis of the actual dimensions using equation (7) and eqals 0.01652 m^3. In addition caluclated weight of metal in the riser was 129.8472Kg.

Analyzing cast freezing time to riser freezing time ratio can give a clear picture about the influence of parameters on the quality of casting.Thus to ensure the solidification shrinkage and macro porosity formation in the trash plate, analysis of melt solidification time in the riser to solidification time in the mold was competed in terms of relative freezing time. The, relative freezing time or freezing ratio (R_F) of riser to casting was then calculated based on modulus method .

$$R_F = \frac{\left(\frac{Volume}{surface\ Area}\right)riser}{\left(\frac{Volume}{surface\ Area}\right)casting} \quad [14] \qquad (15)$$

From the analysis the relative freezing time or freezing ratio obtained was 1.239. Based on the result and as per the designed riser R_F of riser to casting value as well as according to the specific modulus ratio method, volume to area ratio of riser was 0.0466 and that of casting was 0.03761. The volume to area ratio of the riser was 1.239 times greater to the volume to area ratio of the casting, which predicted that the melt in the riser used freezed late by 1.239 times to the freezing of trash plate casting.This relation ship confirmed that the designed riser is sufficient enough to the weigth of metal necessary to feed the plate properly.

From the elements of riser,its base design plays vital role on the quality of casting. Hence**,** the riser base used in trash plate casting was designed based on the size of the riser exit diameter. Hot riser base, in which the riser base placed between the runnr exit and the ingate inlet sections, was used and the ingate was considered as the riser neck section. Appropriate riser base was selected that could be fitted to the riser exit diameter and to accommodate metal in it. The base diametr was 200 mm and height was 80mm. The total volume and weight of the riser base were calculated respectively using equation(16)

$$V_{rb} = \left(\frac{\pi d^2}{4} * h_{rb}\right) \quad [1] \qquad (16)$$

Thus, based on the above method, metal Volume and weight were found to be 0.00251 m^3 and 19.7286Kg respectively.

The other parameter to be considered was the total solidification time that was generally important for determining the soundness of trash plate.The total solidification time of a riser for the $46MnSi_4$ alloy steel trash plate casting was analysed by considering the mold and metal properties using equation(17),

$$t_r = \left[\frac{\pi}{4}\left(\frac{\rho_c \Delta H_f}{T_m - T_o}\right)^2 \left(\frac{1}{(K_m \rho_m C_m)}\right)\right]\left[\frac{(V)}{(A)}\right]^2 \quad [14, 19] \qquad (17)$$

Where, t_r-solidification time of riser, ρ_m, C_m and K_m-are density, specific heat and thermal conductivity of the mould material respectively and H_f- latent heat of solidification, ρ_c-density of liquid metal casting ,V-volume of riser solidified, A- interface area of the riser, T_m -melting temperature (^oc) and T_o - initial temperature of mold wall (^oc) . In this, the properties are assumed to be constant all over the casting process.

Similarly, the solidification period of the trash plate casting was determined based on Chvorinov's rule using Equation (17) above .

From the analysis the total solidification time of both the riser and the casting were 43.9 minutes and 28.6 minutes respectively. These results indicated the total time of solidification of the melt from pouring stage to complete solidification stage. From the result it is seen that the riser solidification period was 15.3 minutes late to that of the trash plate solidification time and could feed the cast effectively as a result of which shrinkage was minimized,possibility of porocity formation and misrun defects were reduced and thus casting quality was improved.

It is clear that temperature lose in the gating system while filling it with molten metal is occurring and has a direct influence on the quality of casting.Thus analysis of this parameters was also considered in this papere. The critical casting process parameters taken through direct observations during metal melting, pouring and part removal activities were pouring temperature(1672^{0}C), melting temperature(1525^{0}C), starting metal temperature (913^{0}C), and atmospheric temperature(20^{0}C). This values were taken in to consideration to determine the effect of temperature lose on misrun formation, fluidity characteristics of the melt and other related physical characteristics. Therefore, the amount of temperature lose of molten 46MnSi$_4$ steel in the gating system was analysed using equation(18) .

$$\Delta T = \frac{Asc)(T_p - T_{mi})(\sqrt{t_p})}{W_t C_i}\sqrt{K_m \rho_m C_m} \qquad [9] \qquad (18)$$

Where, A_{sc}-surface area of the mold channel used (sum of the surface channels of all ingate system (cm^2), T_p-pouring temperature(^{0}C),T_{mi}-initial temperature of the mold(^{0}C), t_p-pouring time(in sec),W_t- weight of the casting and the gating system(kg), C_i - specific heat of liquid metal J/Kg ^{0}C, K_m -thermal conductivity of the mould material , J/se/m ^{0}C, ρ_m,-density of the mould material, Kg/cm^3, C_m - specific heat of the mould material, J/Kg ^{0}C which is given by$\sqrt{K_m \rho_m C_m}$ - Heat diffusivility(J/m^{2}Ks$^{1/2}$).

For thethis particular cast the amount of temperature loss in the gating system elements at the entrance was -21.389 ^{O}C. Hence, the temperature of the molten metal entered to the mold cavity was 1650.6^{O}c. In addition, it is expected that the temperature of the metal could also be further decreased throughout the length of the mold cavity before pouring completed and premature solidification was expected,which in turn lead to reduction of fuluidity that qonsequently be the reason for defect formation.

While solidification of trash plate cast took place heat transfer phenomena was inevitable. Heat transfer may took place from liquid metal to the mold by convection and from the mold to the environment by radiation and to some extent by conduction. Thus, considering three-dimensional (3D) state of flow, the heat flow rate or heat flux per unit area and time required to transfer from liquid casting to mold surfaces, along the mold length (x-direction) using side chill, along the mold height (y-direction) and along the mold width (z-direction) was analyzed using equation(19).

$$Q_t = Q_X + Q_Y + Q_Z = (-K_m A_X \frac{dT}{dX}\text{-}) + -K_m A_Y \frac{dT}{dY} + -K_m A_Z \frac{dT}{dZ} \qquad [18] \qquad (19)$$

Where, Q_t-total heat flow rate, Q_X, Q_Y, Q_Z - Heat flow rates in the x, y and z- directions of the mold,A_X, A_y, A_z - mold face areas in the x, y and z- directions of the mold, **K**m-thermal conductivity of the mouold material and the minus sign (-) indicates that heat transferred in the decreasing temperature direction (high to low) and $\frac{\partial T}{\partial x}, \frac{\partial T}{\partial y},$ and $\frac{\partial T}{\partial z}$,-temperature gradients in the x, y and z- directions of the mold.The result obtained from the analysis was -39.998 KJ/sec. From this result it is understood that metal released high amount of heat per second and subjected to fast cooling (freezing) and fast solidification time which is not desired for steel castings. This may also be connectd with the thin sections of the mold wall and size of the flask used. The reduction of temperature or heat lose led to the formation of shrinkage and mis run due to insufficient feeding of the melt from the riser, especially to outer crosection of the trash plate.

The amount of heat flux transferred from metal to mold by convection was determined using equation (20), [18].

$$q = h\,(T_c - T_o) \qquad (20)$$

Where, q-amount of heat flux (heat transfer rate per unit surface area of the interface), h- film convection heat-transfer coefficient at the metal-mold interface in (w/m^{2}C), T_c -cast end temperature immediately after cavity filling in (^{O}C), To- initial temperature of mould in (^{O}C).

The analysis result shws that the the amount of heat flux was 2,370, 456W/m^2. This amount shows that there was high heat, loss fast cooling process and resulted in the formation of volumetric shrinkage in the cast.

The temperature at any location (X-axis) within the mould as function of time was calculated using equation (21),

$T(x,t) = Tc + (To-Tc)\ erf\left(\frac{x}{2\sqrt{\alpha_{th}(t)}}\right)$ [19] (21)

Where, $\alpha_{th} = \frac{K_m}{C_m \rho_m} = 3.4 * 10^{-7}\ m^2/s$ - thermal diffusivity of mold material (silica sand), t- solidification time and erf- error function (integral).

Table 2: Temperature variation results in mold thickness (+X-direction)

Mold initial temp. (c)	End cast temp. (c)	Time (sec)	X -Distance from casting (m)	Erf $\left(\frac{x}{2\sqrt{\alpha_{th}(t)}}\right)$	T(x,t)
27	1650.6	60	0	0	1650.6
27	1650.6	150	0.015	0.862515	250.22105
27	1650.6	450	0.025	0.84704	275.3454
27	1650.6	650	0.045	0.96768	79.4746
27	1650.6	850	0.07	0.996404	32.8379
27	1650.6	1050	0.09	0.999243	28.2286
27	1650.6	1250	0.11	0.999839	27.26192
27	1650.6	1450	0.13	0.999965	27.0564
27	1650.6	1650	0.15	0.999992	27.01223
27	1650.6	1,717	0.16	0.999997	27.0046

Based on the obtained result after analysis, the temperature distribution (cooling stage) at any locaton with in the mold cross-section is presented in figure 3a.

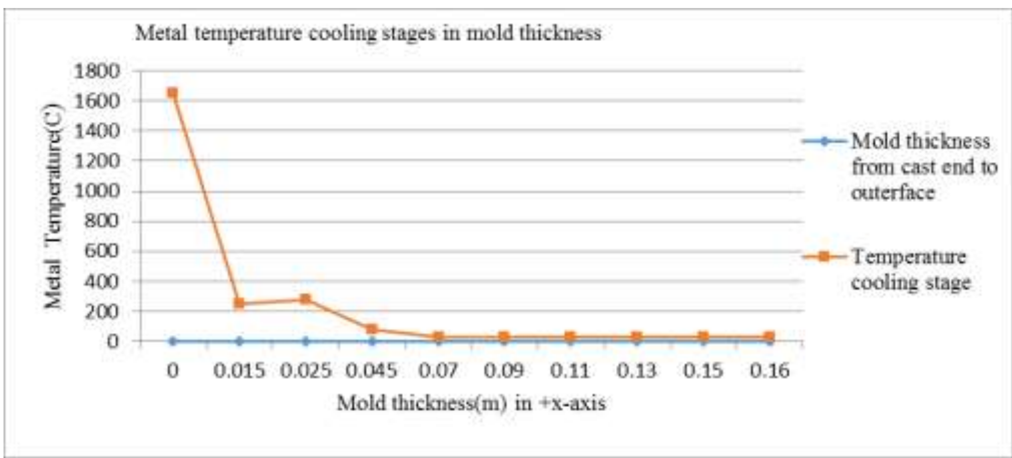

Fig. 3a: Metal Temperature (cooling stages) along mold thickness in +X- direction

The temperature gradient with in the mold at any distance from the casting end to +x direction was determined using equation (22).

$\frac{\partial T}{\partial x} = \frac{T_c - T_o}{\sqrt{\pi \alpha_{th} t}} exp\left(-\frac{x^2}{4t\alpha_{th}}\right)$ [19] (22)

Based on this method the minimum temperature gradient of the molten metal along mold wall in the positive x-direction was determined and magnitude of the gradient results show that reduction during the cooling stage increasesed as the distance increased from the casting end (figure 3b).

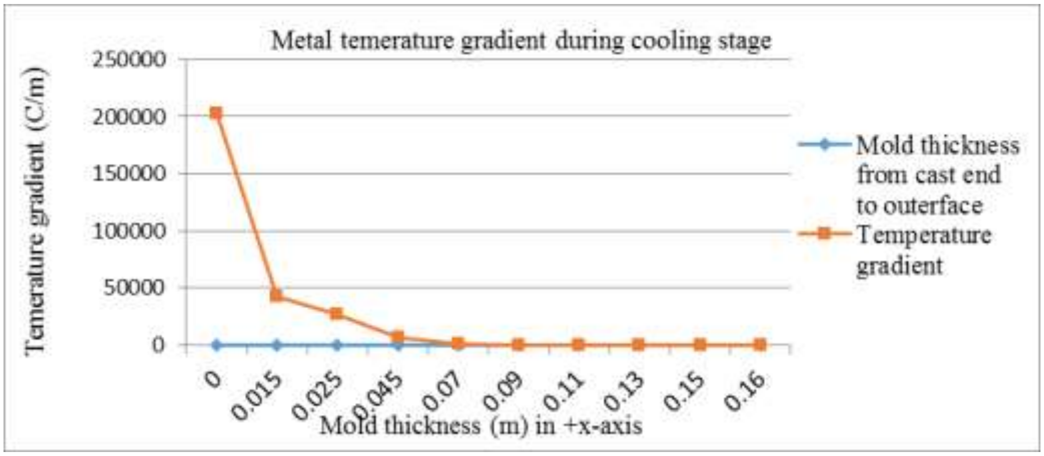

Fig. 3b: Metal Temperature gradient during cooling stage along mold thickness (+X-direction)

From the analysis it was understood that the temperature gradient was dynamically reduced up to 65mm thickness of mold along all the positive directions of mold,which predicted about rapid solidification of melt at thinners sections of the mold.In contrary at mold thickness of 80mm the distribution was slow and relatively uniform. The total heat flux away from the interface of the cast plate in to the mold at a distance was analysed based on the obtained temperature gradients using equation (23), and the results are presented in figure 3c.

$$q_{t\,(m,x,y,z=0)} = K_m \frac{dT}{dx}\Big|_{x=0} + K_m \frac{dT}{dy}\Big|_{y=0} + K_m \frac{dT}{dz}\Big|_{z=0} \quad [19] \qquad (23)$$

Where, Km- thermal conductivity of mold material (silica sand).

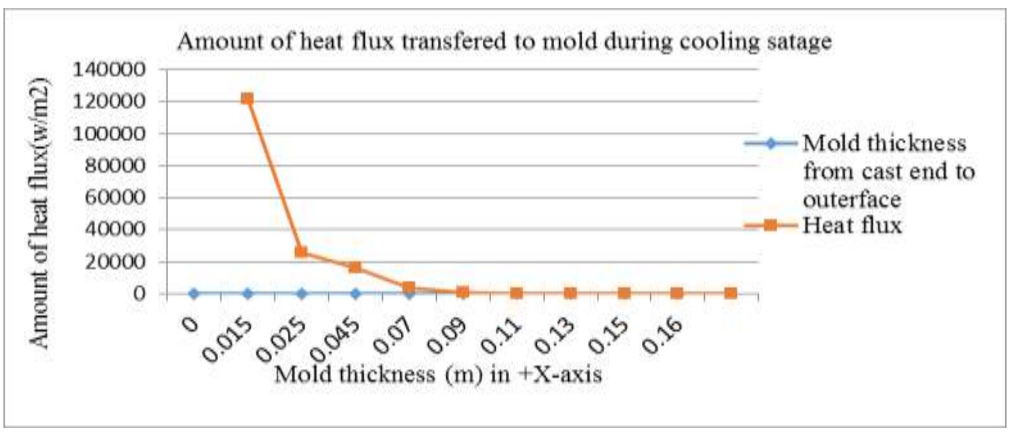

Fig. 3c: Amount of heat flux along the mold thickness in +x-direction

Figure 3c shows amount of heat flux transferred to mold and to environment during the cooling stage. The figure demonstrates that high heat flux was transferred from the metal and absorbed by the mold through all the positive directions.

The temperature variation of molten metal from cavity end to the mold outer surface was considered. The variations obtained were from 1560.6 ^{O}c to 27.0046^{O}c (at distance of x= 160mm) with in 1717seconds and almost the same in all the positive directions of the mold. This confirmed that metal was solidified erlear than the designed time. So the temperature variation during cooling was almost equivalent to the results obtained using numerical and simulation method. Hence, the temperature drop as analyzed by error functione quation, immediately after fiiling the mold,especially at the metal-mold interface was large and at the outer mould surface it was small.

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Optimum parameters' results of trash plate casting

The main gating system elements used to cast the trash plate with the given client specification were determined using the provided gating ratio for steel casting and listed in Table 3.

Table 3: Designed and recommend sizes of the trash plate gating system elements

Element	Shape	Size (cm^2)		Length(cm)	Depth(cm)	Width (cm)	Weight (kg)
		Inlet	Outlet				
Ingate	Rectangular	52	52	5	4	13	2.044
Runner	Rectangular	62.4	62.4	17.25	4.5	13.8	4.95
Sprue	Cylindrical (Frustum)	109.4	83.2	30	-----	-----	16.85
Riser	Cylindrical (Frustum)	490.63	413.27	36.5	-----	-----	219.85

SIMULATION ANALYSIS

Simulation results (fig.4) indicate the temperature variation of the modeled trash plate casting while solidification took place in the transient-thermal analysis that was carried out using ANSYS 14.0 software.

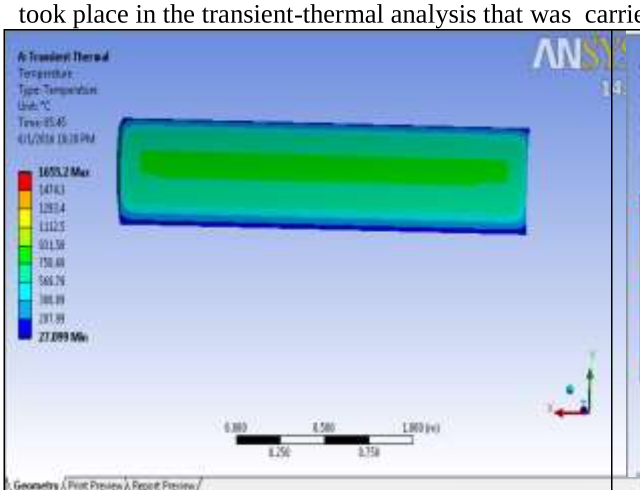

Fig. 4: Simulation results of trash plate casting

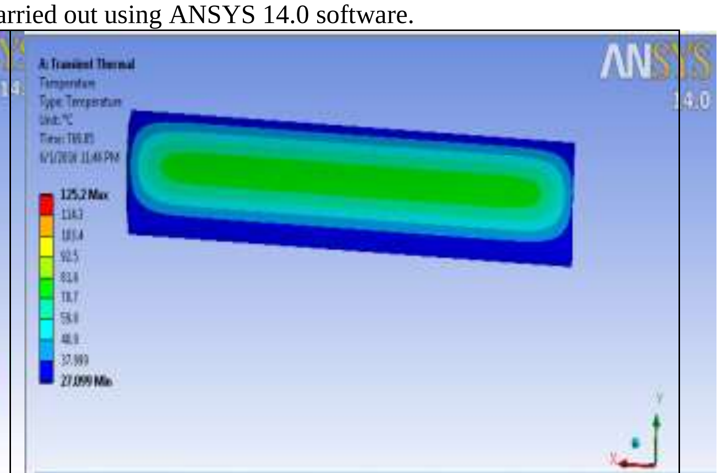

Fig.5: Temperature gradient during solidification of trash plate

The contour bands marked with different colors indicate the cooling stages of molten metal after filling the cavity and taken as the initial temperature of the plate before freezing started. On the cooling stage temperature was reduced from the maximum (hot-color) of 1655.2^{O}c towards the minimum (blue-color) of 27.099^{O}c. Also the simulation result shows the total time required to complete solidification of molten metal in the mold cavity which was 769.05 seconds(figure7). Simulation was performed by assumming the metal in the cavity with initial temperature of 1650.6^{O}C, temperature difference between the pouring temperature and the estimated temperature loss, and also the mold initial temperature was 27^{O}C. The effect of convection in the metal-mold– interface was taken in to account and hence the effect of the mold material (silica sand) on the transient-thermal analysis was not considered. Hence, the simulation results were considered due to the effect of molecular interactions while transferring from liquid state-to-solid state only at the metal-mold interface. Finally, simulation results predicted that the overall solidification period of the plate was rapid and this caused volumetric solidification shrinkage. This inturrn lead to misrun and porosity formation in the trash plate casting.

CONCLUSION

The results have shown that the applied methods for determination of the casting defects and the optimum settings of factors were achieved successfully and the following conclusions can be drawn:

1. The numerical calculated results have shown that the misrun, and volumetric solidification shrinkage defects occurred in the trash plate castings were due to the improper utilization of patterns with less than 2% shrinkage allowance and the in accurate design of gating system elements for the given steel.
2. The experimental results have shown that the sand sintering problem and porosity defects occurred in the trash plate castings were due to the weak sintering strength of fine mixed molding silica sand used in casting process of the plates in the foundry industry.
3. The simulation results have shown that volumetric solidification shrinkage, misrun and porosity defects occurred in the plate castings were due to the improper metal compensation to outer most sides which resulted from the fast cooling (freezing) period of the metal in the cavity.

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