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Feeding of Hollow Cylindrical Castings

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ABSTRACT

The paper deals with the methodology and the manufacturing process used to successfully develop a long cylindrical casting, called the Hollow Shaft. Both experience as well as a rough estimate of the Niyama Criterion indicated strong possibilities of a centerline shrinkage The methodology was based on (1) The Shape Factor and Feeding Distance formulae specified in the SFSA Feeding and Risering Guidelines for Steel Castings[1], (2) Use of a padding and (3) Heuver's circle method. A formula for assessing the length of the critical mushy zone derived from the Niyama Criterion has been developed. The hollow cylinder was cast without any internal or external defects.

Keywords :Feeding Distance, Hollow Shaft, microporosity, mushy, Niyama,

INTRODUCTION

During the year 2000 the author operated a modern no-bake foundry located near Kolkata (India) producing sophisticated carbon and alloy steel castings, based on the use of phenolic urethene binder. A development order was executed for a low alloy steel Hollow Shaft casting for a German manufacturer of high–speed locomotives. These castings were subjected to severe stresses in high speed service, and therefore had to meet strict norms for internal soundness and metallurgical properties The Hollow Shaft (Fig. 1) was basically a thin-walled cylinder of internal diameter 224 mm, with a uniform thickness, except at the base at one end (Fig. 2)The overall length was 1435 mm. Such cylinders were normally prone to internal centerline shrinkage, which was unacceptable. A major factor is the blockage of feed metal flow which result in micro-porosity or voids in the solid casting. These voids add up to produce a centerline shrinkage.

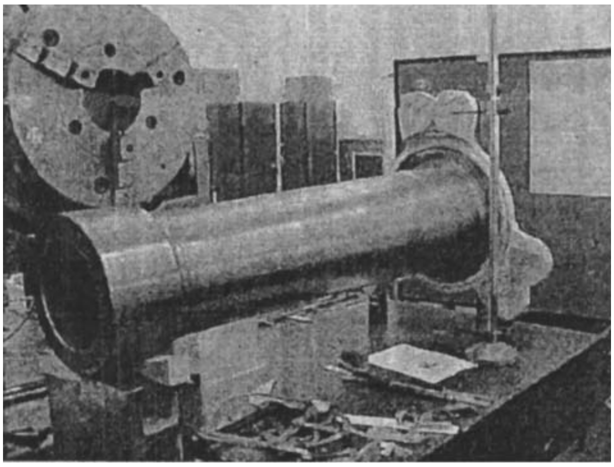

Fig. 1 : Hollow Shaft Casting

FEEDING

Feeding covers methods adopted to produce castings without shrinkage defects. In the case of solid solution alloys like steel, this is achieved by ensuring that the feeders solidify later than the castings. Simply stated, a feeder must contain enough liquid metal to compensate for the volume contraction occurring while the casting cools from the liquidus to the solidus temperatures.

Computerised methods for deriving riser sizes based on relative solidification times are readily available .One of the earliest attempt at mathematical riser sizing was derived from Chvorinov's equation, which established a relationship between the solidification time of a casting to its volume-to-surface area ratio .This ratio was called the modulus of solidification. Wlodawer [2] developed extensive data based on this modulus concept, for determination of riser sizes, with a twenty percent safety factor. Empirically, Caine [3], using his FreezingRatioand Bishop et al [4], using the ShapeFactorratiodeveloped formulae and curves prescribing riser diameters for various casting volumes, shapes and sizes. The Steel Founders' Society of America (SFSA) has

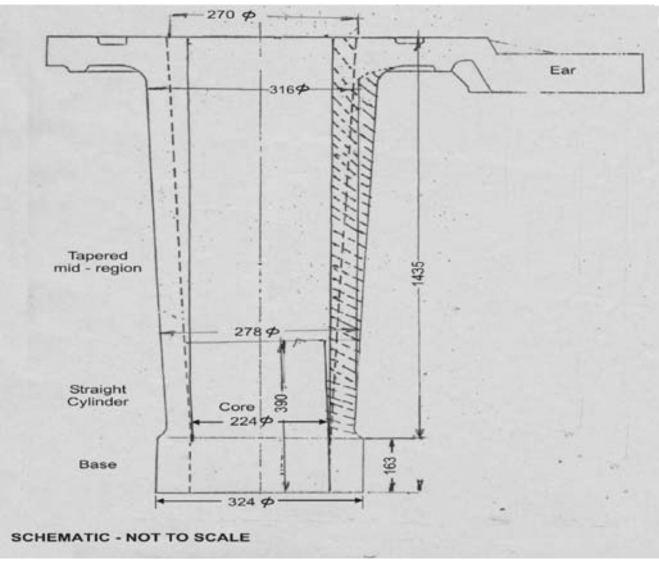

Fig. 2 : Critical Dimensions of the Hollow Shaft Casting

recommended the method based on Bishop's Freezing Ratio for determining riser diameters in their monogram titled "The Feeding and Risering Guidelines for Steel Castings 2001" [1].

FEEDING DISTANCE

Obtaining a sound casting will require that the riser not only contains adequate volume of liquid metal, but is also positioned in such a way that the liquid is able to flow throughout the volume of the casting, till solidification is complete. Determination of the feeding distance is therefore an important consideration in obtaining sound hollow cylindrical castings.

The feeding distance is defined as the length from the edge of the riser to that point on a casting which can be fed without micro porosity or shrinkage; such that they cannot be detected on the X Ray plate (in radiographic testing) at two percent sensitivity.

The earliest significant effort at determining feeding distances was due to Myskowski, Bishop and Pellini [Ref. 4] Assuming favorable temperature gradients, the solidification front, described in detail later, moves from the end of the casting towards the riser, The distance covered by the solidification front would be equal to the feeding distance of the riser, FD, when the casting is sound. The formula for FD would then be as follows:

$$FD = RZL + EZL \qquad (1)$$

where RZL = Riser Zone Length, and EZL = End Zone Length

The SFSA Guidelines [1] have given comprehensive explanation / illustration of the two zones.

Recent studies by Niyama et al [5] on the effect of temperature gradient, have clarified relationships between temperature gradients, cooling time and feeding distances. Carlson et al [6] have presented new formulae for feeding distances based on consideration of the Niyama Criterion. The zonal lengths, and the Feeding Distances have been evaluated at the University of IOWA, in terms of the Width-to-Thickness ratio of the castings, assuming plate like geometrics, for various configurations of side risers, top risers, chilling etc. The values have been incorporated in the SFSA Guidelines [1].

A comment on the role of the riser size is appropriate at this stage. The soundness of a casting depends on (1) its solidification time and (2) its feeding distance, FD. The formulae for FD, in effect, indicate a critical value, since if the length of the casting is longer, it will show porosity. In that case the solution adopted by the author was to increase the diameter of the riser (and hence its height proportionately). In fact, whenever the FD was short of the casting length, the author had always increased the riser diameter first before attempting other solutions. Since a properly designed riser should store liquid metal at the highest temperature increasing its size did increase the RZL, with corresponding elimination of porosity.

THERMAL GRADIENTS

Without favourable thermal gradients no castings poured in an eutectic alloy can be produced free of porosity or shrinkage, even with an adequate riser. Typically in a solid solution alloy, dendrites grow during solidification. When the tips of the growing dendrites meet, they block the passage of liquid metal. Thus, an adverse temperature gradient can render even an adequate riser, with safety factor, incapable of eliminating micro-shrinkage.

Feeding systems, consisting of a feeder attached to its casting, must be such, that assuming hot metal is poured through the riser, the solidification starts at the end edge or a chilled region of the casting and then proceeds towards the riser; so that the last metal to solidify is within the riser (Fig. 3) This is easily achieved when the temperature gradients allow the creation of a tapering channel starting from the end edge of the cooling casting , and then opening up towards the feeder , as shown n Fig (4) . If the length of the casting, FL, is larger than FD, a centerline shrinkage or micro-porosity will occur .in the mushy zone, (Fig 3). This defect will not occur when the length of the mushy zone satisfies Equation (9) as explained in the following sections.

MUSHY ZONE

During solidification, the cooling casting would contain (1) a solid zone, frozen against the mould wall, and (2) a fully liquid zone at the center.; (3) in between there would be a liquid-solid or mushy zone where dendrites form and grow (Fig. 3). A thin layer of liquid atoms, a few atoms thick, at the solid-liquid interface constitute the solidification front The distance traveled by this front, and its velocity within the cooling casting during solidification, is dependent on the temperature gradients in the liquid as well as the undercooling governing nucleation.

In most metals and alloys, dendritic growth forms the basis of the solidification process. The origin of this growth is the

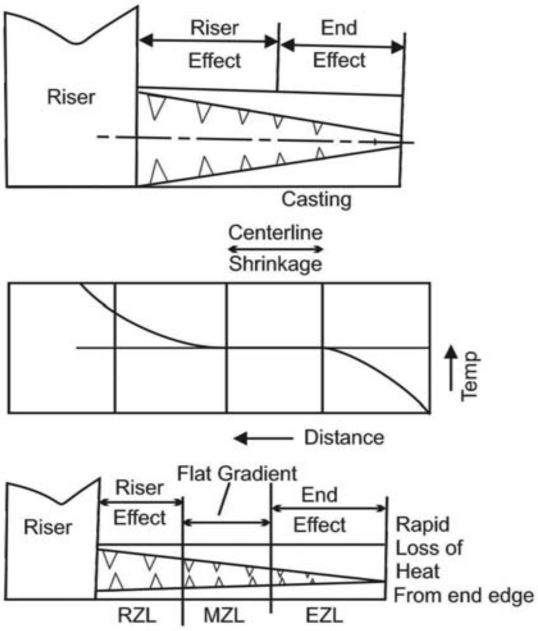

Fig. 3 : Feed Channels within a solidifying casting, showing flat temperature gradient at centre (bottom) without and absence of flat temperature gradient (top)

rejection of the solute by the solidifying layers The rejected solute accumulates at the liquid-solid interface lowering the freezing temperatures. This constitutional undercooling sustains dendritic growth. The thermal gradients resulting from the loss of heat to the mould leads to a difference in density in the liquid metal, There is also a change in liquid composition. These factors lead to, under the influence of gravity, a buoyancy driven convective flow.

During initial solidification the dendrites are surrounded by liquid metal. so that while the solidification front moves from the casting edge towards the riser, the volume contraction is automatically compensated. Significant mass transfer of liquid feed metal occurs as the solid fraction increases. Gradually resistance to flow develops. Finally when the solid front reaches a high value, the dendritic structure spreads throughout the bulk of the liquid metal, The flow of liquid feed metal ultimately becomes virtually impossible . The point at which flow resistance starts, namely when significant mass feeding finishes, can be called the solid fraction for Coherency ; while the point at which feed metal flow ceases has been called the solid fraction for Rigidity or the critical solid fraction.

Between these solid fractions, represented by the point of Coherency and the point of Rigidity, is the mushy zone. The flow of feed metal through this zone depends on its permeability, which is proportional to the degree of solidification. When the permeability is zero, the feeder ceases to function and the casting will contain micro porosity, since the entire trapped metal within the inter-dendrite region will solidify leaving voids. Therefore the length of the mushy zone after the critical solid fraction is reached, or the Critical Mushy Zone (CMZL) is an important factor as it will contain the micro porosity. If CMZL = 0, then there will be no micro porosity.

NIYAMA CRITERION/NIYAMA LENGTH

The key finding of Niyama et al [5], is that the critical temperature gradient G, at which porosity forms is proportional to $1/\sqrt{t}$, where t = solidification time .If the cooling rate R = (liquidus temperature – solidus temperature / solidification time), Then the Niyama Criterion N can then be stated as,

$$G/\sqrt{R} > \text{constant} \qquad (2)$$

Where G is the temperature gradient in K°/mm and R the cooling rate in K° /second.

The foundryman can use the SFSA Guidelines for checking whether the Feeding Distance is smaller than the casting length to be fed. In which case his casting will contain a critical mushy zone. The Niyama value (N) can be used for checking whether this mushy zone will give porosity. For this purpose the relationship between the length of the mushy zone with the Niyama value, N, has to established.

In order to develop a relation, an equation has been taken from a similar eutectic phenomena. namely the equations presented by Kim –Dar Li et al in their paper on A356 alloy [7] relating the pressure drop with the mushy zone phenomena common to eutectic alloys. The local length of the mushy zone l in mm at a location in the casting is given by this worker as

$$l = \Delta T / G \qquad (3)$$

Where ΔT = solidification temperature range in K° and G is the thermal gradient, K° / mm Then, the local solidification time t in seconds can be represented as

$$t = \Delta T / G{*}Vs \qquad (4)$$

Where Vs mm/sec is the solidus velocity. And t sec is the solidification time .

Considering, $N = G/\sqrt{R}$, and substituting for G from equation(3), and putting $R = \Delta T/t$, we get;

$$l = \sqrt{\Delta T{*}t} / N \qquad (5)$$

With reference to Fig. 3 of this paper, and to Figs. 12 and 14 given in the SFSA Guidelines, if FL is the length of the casting which requires to be fed to soundness, then from Equation 1,

$$FL = RZL + l + EZL = FD + l \qquad (6)$$

The casting length will be sound, if FL =FD.Hence, from equation (5) & (6), for elimination of porosity,

$$l = \sqrt{\Delta T{*}t} / N = 0 \qquad (7)$$

This is unrealistic unless an unrealistic Cooling Rate is considered which is impracticable. Therefore an empirical value of N, which Carlson et al [6] has determined as a *thresholdvalue,* has been considered.

For soundness, the threshold Niyama value established by Carlson et al [6] is

$$N = 0.1\ K^{1/2}\, s^{1/2}\, mm^{-1}$$

In other words, when $N \leq 0.1.>$ Constant, the mushy zone length l should be free of micro porosity This would be an empirical assumption based on the work of Carlson et al. Since the *threshold* value of N has been used, this length is also the *threshold* length over which micro porosity will result. We have called this length as CMZL or the Critical Mushy Zone Length.

Substituting N=0.1 in Equation n.(7) , the critical mushy zone or the *thresholdlengthover* which feed metal flow may be obstructed giving porosity is obtained from

$$l = 10\sqrt{\Delta T}\ {*}t \qquad (8)$$

For convenience if we call this length l as *thresholdor Niyama Length*, the equation(6)) giving the length of a casting FL that can be fed to soundness can be written as :

FL = RZL +EZL+ Niyama Length = FD + Niyama Length

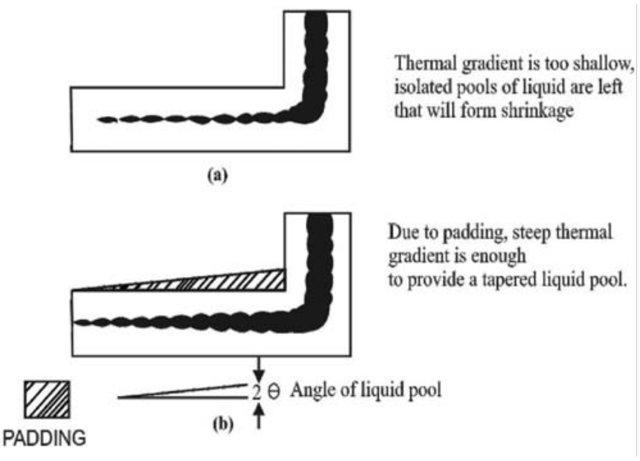

Fig. 4 : Illustration of a plate like casting (a) with and (b) Porosity (adapted from [8])

(9)

This relationship has been used to check the FL for the Hollow Shaft.

DESIGN OF THE FEEDING SYSTEM FOR THE HOLLOW SHAFT

In case the length of the casting exceeds the Feeding Distance, .the methods engineer employs a number of means to ensure directional solidification. All these methods have been used in this case.

1. Use of chills to initiate directional solidification.
2. Simultaneously top risering and top pouring can be introduced to create favourable temperature gradients
3. Provide a taper or padding, so that feed metal channels remain open during solidification
4. For obtaining fast solidification zircon sand, with larger thermal conductivity, can be used as facing in both moulds and cores.

The overall dimensions of the part, with the machine allowance are shown in the drawing in Fig. (2). For methoding, the part has been considered as an assemblage of three sections .At the bottom is the heavy cylindrical Base of inside diameter 224 mm, height 165 and thickness 50 mm, This inside diameter remains constant upto a height of 390 mm, like a straight walled cylinder, with a thickness of 27 mm. Thereafter, the outside diameter increases from 278 to 308 mm namely with a 15 mm taper. The inside diameter similarly increases from 224 to 270.. Thus we can consider a cylinder, straight upto a length of 390 mm and then opening up, to be resting on the bottom Base. The topmost portion is a flange of average thickness 50 mm with three "ears". Right at the beginning it was decided to cast the piece vertically, such that the most important portion, which is the base gear, is at the bottom. (drag). The riser positions have been shown in Fig (5). By splitting the Base and opening it up like a plate, its size would be 50mm thick, with width 391, and the length FL, to be fed, would be 850 mm. The riser as positioned in Fig. (5) could be considered as top feeding on the plate so that the W/T ratio is approx 17. Based on this ratio, using Shape Factor and FD curves given in the SFSA Guidelines [1], a riser diameter of 200 mm was selected. Considering various configuration namely lateral top feeding, side feeding, top feeding, the SFSA Guidelines give FD/T ratio from 6 to 9. Taking the ratio as 6, to be conservative, the feeding circle should be riser diameter 200 mm plus 2 x 6 x50 or 800.mm The Niyama length, calculated on assumed values for t and ΔT is 250. The length FL which is, 850 mm is less than the value of FD+ Niyamalengthequal to 800 + 250 or 1050 mm. Hence the base, as expected, was free of micro porosity after casting.

PADDING

The W/T ratio of the thin walled cylindrical mid -region of the Hollow Shaft which was very high (approx 37), is not covered by the Guidelines. [1]. Indeed the best method of feeding such thin cylinders was to provide a padding. In this case the casting length was larger than the total of FD + *Niyama Length* and hence was bound to show internal porosity if no padding was provided.

By simply maintaining the internal core diameter as 224 from the bottom to the flange base, a metal padding was automatically obtained. The thickness of this padding as a percentage of the length was approximately 2 percent. This was considered adequate for a top riser Fig. (5) to feed the casting along its entire length, when cast vertically. As a result of pouring hot metal through the riser, followed by addition of thermix powder, and chilling at the bottom region a favourable temperature gradient from the top riser downwards was ensured. In fact it is possible to feed theoretically unlimited distances by using the padding; the limitation being only the capacity of the feeder to contain the necessary volume of liquid metal throughout solidification. Due to the padding, which has to be machined off, the yield

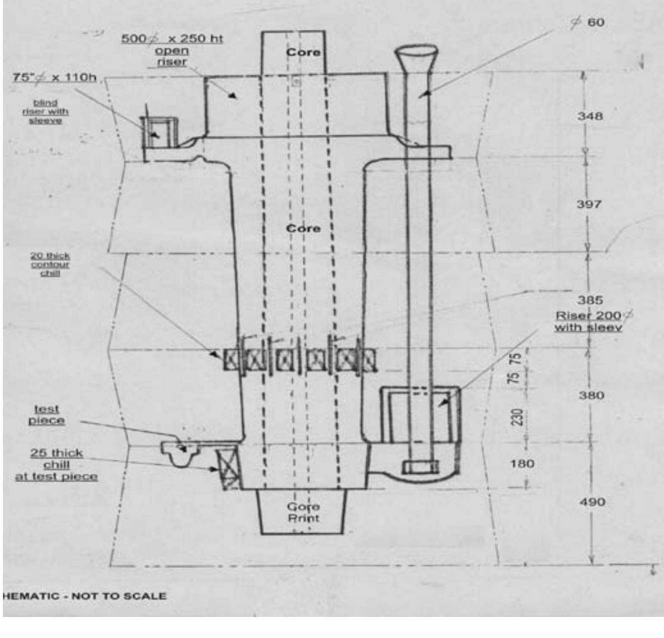

Fig. 5 : Feeding Method for the Hollow Shaft Casting

got reduced; while extra cost of machining was incurred But this was compensated by obtaining the Hollow Shaft casting free from centerline shrinkage, The taper to be given on the padding is most critical. Assuming that feeding occurs as long as the taper of the liquid channel is greater than the critical angle θ. (Fig 4) the value of the angle "θ" for steel plates as computed by Sigforth and Wang [8] lies between 2 to 5 degrees centigrade. The taper obtaining on the vertical Shaft casting was about 2 percent.

HEUVER'S CIRCLE METHOD

Examples of the use of Hot spot or Heuver's circle can be found in Wlodawer's book. [2] This is a very useful method for feeding padded castings with tapering thicknesses. The diameter of the Heuvers circle, inscribed within the smallest section is gradually increased till the riser. .The riser sizing thereafter can be done based on the modulus ratio.

This method was used for prescribing the Riser on the Flange. The hot-spot diameter, which is the same as the Heuver's circle diameter, at the junction of the top flange with the cylindrical shaft is 140 mm. The internal core diameter through the top riser was reduced to 200 mm, so that putting an open top riser of 500 mm diameter, provided enough storage of liquid feed metal.

Metal was poured through a refractory sprue through the bottom riser, the last portion of the hot metal was poured through the top riser. Therafter, after a gap of about five minutes, exothermic powder addition was done in batches at intervals. This produced a positive condition for directional solidification.

In order to prevent the top riser from feeding the bottom one, it was essential to position chills, 25 mm thick, just above the top of the bottom riser . Limiting the thickness of the padding was possible , because of bottom chilling combined with the top pouring of the riser, and the post-pouring addition of exothermic powder.

MANUFACTURING

Fig. (6) shows the method of moulding the casting. which was cast vertically. The mould consisted of five "cakes", of 1020 mm x 900 mm size , made of no-bake sand, assembled vertically in the moulding pit and securely clamped to a cast iron bottom plate, with bolt and nut arrangement, as shown in the figure. The core, made out of no-bake sand, tightly packed around a mild steel pipe wound over with straw ropes, was first assembled in the bottom-most cake and tied down by wire rigging. The moulds were thereafter assembled using a spirit level to maintain both vertical and horizontal alignments. Shaped thermocole chaplets were used to maintain the vertical alignment. The entire assembly was housed in 1100 mm square moulding boxes; the intervening gap being filled with loosely packed sand.

Fine zircon sand (AFS No 200) was used as facing, as stated above, both for the mold and core. The backing sand was a mix of fresh silica and reclaimed sand in ratio 50:50. All cakes and cores were washed with zircon wash and thereafter dried in the electric tunnel furnace for half an hour, at around 180 degree centigrade.

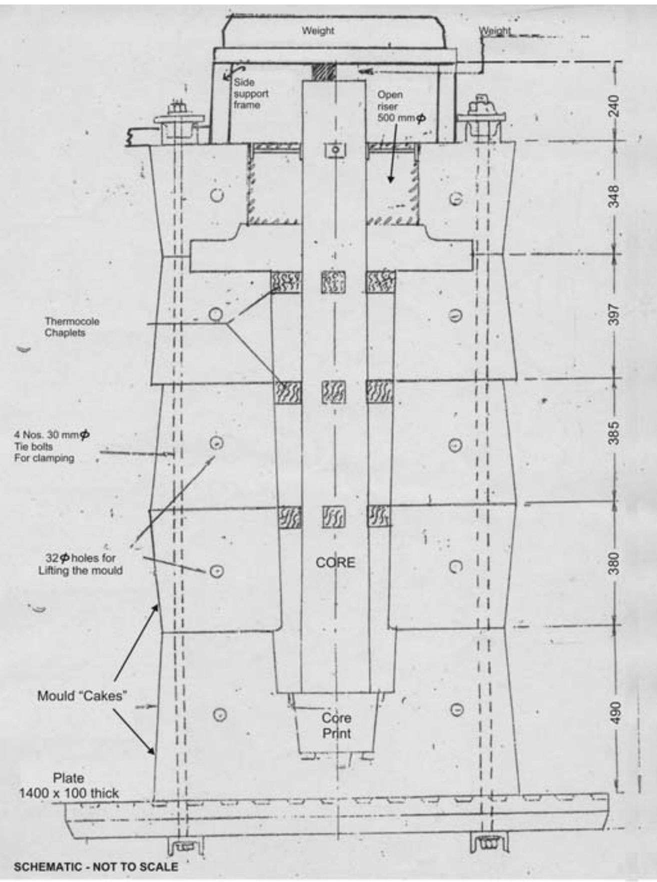

Fig. 6 : Closed mould configuration, showing assembly of cores

MELTING AND POURING

Pouring was started at a temperature of 1600 ° C and once the metal reached the bottom of the riser, the ladle was shifted to enable top pouring. Fresh cold rolled steel punchings scrap and alloy additions were melted in the induction furnace to give the following metal specification:

C=0.17%., Si=0.49%, Mn =0.87%, P=0.017%, S=0.011%, Cr=0.70%, Mo = 0.52 & Ni= 0.80 %. The weight of the metal poured was 1000 kg, and that of the machined casting was 600 kg. The yield was 60 percent, and was considered unavoidable since a high degree of internal soundness was specified.

HEAT-TREATMENT

After shakeout, the casting was homogenized at 920 ºC for 6 hours and then risers were gas-cut and the casting fettled, An initial proof machining was done and thereafter the casting was heated vertically in electric furnace at 910 ºC, for 6 hours and then oil quenched. This was followed by tempering at 600/610 ºC for 6 hours followed by cooling in furnace. The final hardness obtained was 175/179 BHN, along with the following critical properties: UTS 832 N/mm², YS 703 N/mm², Impact at 20 ºC below zero = 42 J and at 40 ºC below zero = 28 J

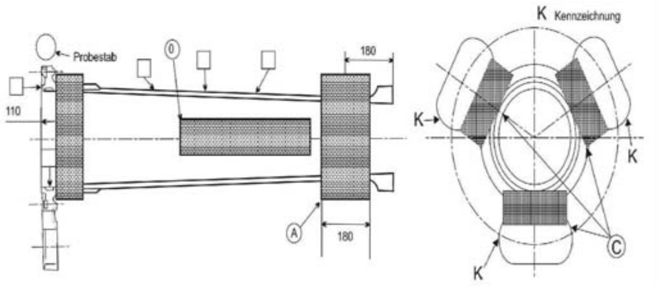

Fig. 7 : Critical regions of the Hollow Shaft Casting are shaded These shaded portions were free of shrinkage or porosity as checked by X-Ray

QUALITY TEST RESULTS

The casting surface, in proof-machined condition, was checked by Magnetic Crack Detecton methods and was found free from cracks, blowholes and/or pinholes .Radiographic examination was carried out with particular attention to the critical areas which were marked by the client and shown in Fig. 7. The X Ray check reported that ASTM level 1 standard was met in respect of shrinkage and porosity at 2 percent sensitivity.

The first casting was fully machined and was found free of defects on the critical regions. Minor surface pin-holes were noted at the junction of the “ears” with the cylinder. This was due to using a 100 percent Zircon sand core at the region, with inadequate venting. These cores were eliminated, after incorporating the casting contours as a part of the pattern (self-core) .

Additionally, slag and fine localized pinholes were noticed. at the centers of the ears.. The chills at the region were eliminated and 75 mm diameter risers with exothermic sleeves were instead put on the ears, which drew off the slag/gas. The final methoding gave a sound casting without any centerline shrinkage.

CONCLUSION

Long hollow cylinders, with thin walls, normally show centerline shrinkage This defect occurs at the mushy zone, beyond the feeding ranges of the riser, or the cooling action associated with the end edges of the castings. To avoid such defects padding was used to avoid flat temperature gradients occurring within mushy zones... The Niyama length concept has been used to quantify the critical length of these zones, and was used in methoding the Hollow Shaft. This casting was produced free of porosity and centerline shrinkage using the methods described.

REFERENCES

1. Steel Founders’ Society of America : Feeding & Risering Guidelines for Steel Castings , 2001
2. Wlodawer R: Directional Solidification of Steel Castings, Pergamon Press, First English Edition pp40 -70, 1966
3. Caine J.B. :A Theoretical Approach to the Problem of Dimensioning Risers Transactions of American Foundry Society, Vol 56, pp492 – 501.1948 and Vol 57p66, 1949
4. Myskowski E.T.,Bishop H,S, and Pellini W. S. : A Simplified Method for Determining Riser Dimensions , Transactions of American Foundry Society, Vol 63,p271,1055
5. Niyama E, Uchida T, Mrikawa M and Saito S.:A Method of Shrinkage Prediction and its Application to Steel Casting Practice. AFS International Cast Metals journal Vol 7, No 3, pp52 – 63, September 1982.
6. Carlson K.D., Ou S, Hardin R.A. and Beckermann C: Developement of New Feeding Distance Rules Using Casting Simulation Metallurgical and Material s Transaction Vol 33 B, pp 731-39, 2002
7. Kim– Dar Li, Ming – Cheng and Edward Chang: Effect of pressure on the Feeding Behaviour of A356 Alloy in Low – Pressure Casting American Foundry Society Transactions, paper N0 01-026, 2001
8. Sigworth G.K. and Wang C: Mechanism of Porosity Formation during Solidification; A Theoretical Analysis, Metallurgical and Materials Transactions, B, Vol. 24B, pp 349 – 364 1993