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DESIGN OF THE CRUSHER JAW USING HADFIELD STEEL: GATING AND RISERING

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ABSTRACT

The crusher jaw is a wear component for stone crushing and made of Hadfield Steel. It is subjected to high impact loading in operation and hence must be manufactured or cast with minimal shrinkage porosity. Using a 1,100 kg crusher jaw, gating and risering was designed by consideration of the solidification time of the casting, the feedable weight and the feeding range employing the use of Chvorinnov's rule, Pellini and Bishop's rules and the Shouzhu new feeding distance rule. After iterating through the process, the design yielded a gating with sprue diameter of 50 mm and four (4) cylindrical risers of diameter 250 mm and height 400 mm. The overall dimension of the crusher jaw was 1650 mm × 1085 mm × 110mm with a tooth depth of 45 mm and back grooves of 20 mm. The crusher jaw also had a calculated weight (mass) of 1100kg. However, due to the casting teeth profile and weight reduction recesses, the risers were combined as oval risers and set as side risers to feed centrally along the teeth axis.

1. INTRODUCTION

Founding is a very valuable technology for the production of metal parts, but often, only omnibus principles are provided in the literature which makes the actual practice a daunting exercise. The production of a casting that meets both compositional and mechanical properties passes through six founding processes which include pattern making, moulding, melting, casting, fettling and heat treatment, each of which introduces its own production difficulties and defects. Consequently, each casting must be uniquely designed to mitigate or obviate the defects associated with the different processes as it relates to the casting. Defects in castings are the main reason for the design of castings but though there are general principles, the application of these basic principles are not generalizable; each casting must be treated independently and distinctly. The design depends on the size of the casting, the quality or grade of the steel and the desired mechanical properties after production. The aim of this work is to apply the general principles in founding to the production of a specific grade of steel known as Hadfield steel, which is one of the more than six thousand grades of steels currently in existence (All Metals, 2012).

Castings design is mainly an industry based design process and because it is unique to every casting, there is little published work that could treat castings design in the manner presented in this work. The general principles of castings design like the design of risers and gatings, moulding and melting and heat treated were employed (Beele, 1996). However, the treatment was specific to the steel alloy, Hadfield steel; and also specific to the size used in the design. There is limited knowledge of foundry practice in Nigeria, hence this study will be a useful contribution to foundry practice.

2. MATERIALS AND METHODS

2.1. Material Selection

Hadfield Steel also known as High Carbon, High Manganese steel has a composition of Carbon (C), (0.8- 1.2%); Manganese (Mn), (11.0-14.0%); and Silicon (Si), (0.5 -0.8%) and other trace elements, which, in its as-quenched condition, contains mostly retained austenite (VEW, 1998, Kuyucak, 2005). It is used for processes requiring high impact operations and hence it is used as the material of construction of crusher jaws.

2.2. Detail Design

2.2.1. Gating system design

Gating system design involved determining the size of the gate that will ensure the filling of the casting before solidification. Figure 1 provides the dimensions of the crusher jaw used in the study.

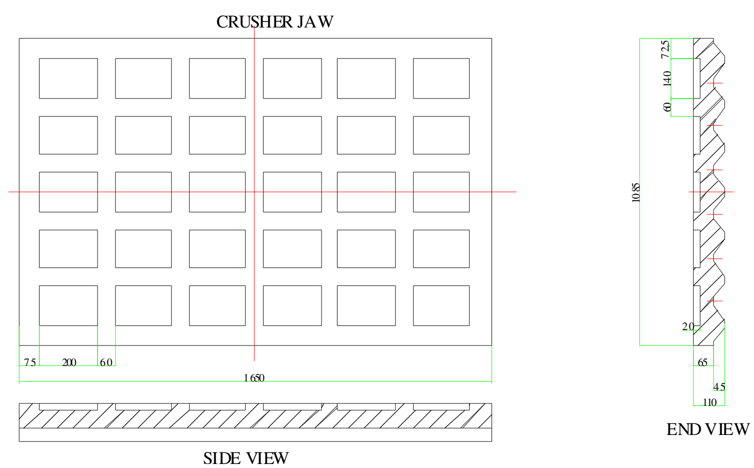

Figure 1: Crusher jaw

The gating system for the crusher jaw is designed to provide directional flow and to fill the mould before the onset of solidification. Gating design was done with the use of Chvorinov's rule to determine the solidification time of the thinnest section of the jaw (Jelinek and Ellbel, 2010).This is regarded as the time within which the mould must be filled, else, the casting solidifies and create cold-shut or shut-run. Chvorinov's rule which gives the solidification time, t_s is minutes/m^2 is given as:

$$t_s = B\left(\frac{V}{A}\right)^n \qquad (1)$$

Where A = Surface area of Casting; B = Mould constant for Chvorinov's rule; V = Volume of casting; n = Constant for Chvorinov's rule.

The mould constant B depends on density, thermal conductivity, heat capacity, wall thickness of metal, heat of fusion and superheat and is given by Equation 2:

$$B = \left[\frac{\rho_m L}{(T_m - T_o)}\right]^2 \left[\frac{\pi}{4k_t \rho c}\right]\left[1 - \left(\frac{c_m \Delta T_s}{L}\right)\right]\left(\frac{1m}{60Sec}\right)\left(\frac{1m}{100{,}000cm^2}\right) \qquad (2)$$

Where L= Length of neck, ρ_m = Density of metal, T_m = Melting temperature of liquid metal, T_o = Initial temperature of mould, k_t= Thermal conductivity of mould and ρ = Density of mould. The values of these parameters for Hadfield Steel are: T_m = 1580°C; T_o = 1450°C; ρ_m = 7860 kg/m^3; L = 211 kJ/kg; k = 0.6 W/m-°C; ρ = 1500 kg/m^3; c_m = 0.46 kJ/kg-°C; c = 1.16 kJ/kg-°C; $\Delta T_s = T_{pour} - T_m$ = 1580°C – 1450°C = 130°C, which when substituted into equation 2 would give the value of B = 0.001569.

The thinnest section of this plate-like body is the section of the trough of the teeth while the thickest section is the crest of the teeth. The parameter, V/A, is the modulus of the casting at the thinnest section, which by the plate-shape of the component is half the thickness at the section. Therefore, V/A = 55/2 and n = 2. Equation (1) gives the value of t_s=0.79 min/m^2 or 47.7 sec/m^2. The quasi-empirical method based on experimental result gives the solidification time formula for steel as (Rashid, 2013):

$$t_s = k\sqrt{W} \qquad (3)$$

Where W = Weight of casting

According to Rashid (2013), k values experimentally determined for steel are 1.2 for 45.5 kg (100lb) and 0.4 for 45,500kg (100,000 lb); which can be interpolated for the casting weight of 1100 kg (2420 lb) to yield k = 1.01. Equation (3) results in a value of t_s= 49.6 seconds/m^2. Therefore, the solidification time calculated using Chvorinov's rule is within acceptable limit. This solidification time was utilized in the determination of the gating system for the casting (Colton, 2011).

Figure 2 shows the gating system, which consist of the pouring basin, down-sprue, the runner and the in-gate. The modified Bernoulli's Equation, was used to estimate the velocity of the sprue and inlet gate as:

Velocity at the base of the sprue:

$$\upsilon_s = \text{Velocity of the inlet gate } \upsilon_g = \sqrt{2gh_s} \qquad (4)$$

h_s = Base height of sprue

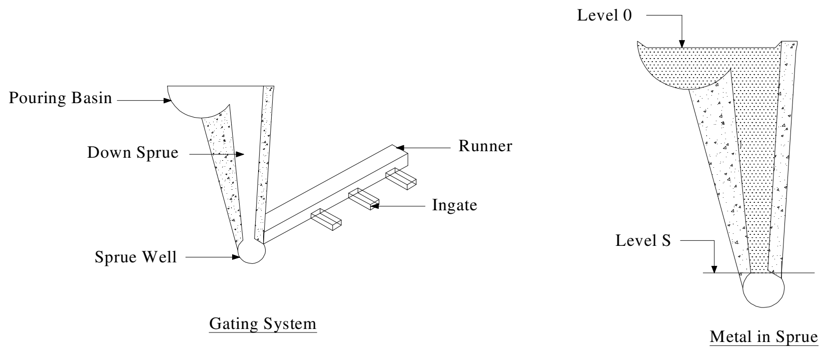

Figure 2: Gating system for application of Bernoulli's equation

The design of gating also considers the available mould boxes and the placement of the pattern in the mould. In this case, the available mould boxes are the pair designated 2400 x 1600 x 400/400, which means that the cope and drag each has dimensions of length, 2400mm, width, 1600mm and height, 400mm. In order to produce the teeth profiles of self-core, the pattern will be in the drag; hence the runner and ingates will also be in the drag. The pouring basin and the down-sprue will be in the cope, which will give the height to sprue base from basin top as 400mm. The fluid velocity at sprue base from Equation (4) is $v_s = \upsilon_g = \sqrt{2\mathrm{gh}_s} = \sqrt{2x10x0.4} = \upsilon_s$ = 2.8m/s using h = 400mm.

Volume of` cast:

$$V_c = A_g \upsilon_g T_d \tag{5}$$

Where A_g = area of gate; V_g= velocity at gate; T_d= discharge time

Hence:

$$A_g = \frac{V_c}{\upsilon_g T_d} = \frac{V_c}{\upsilon_g t_s} = \quad A_g = \frac{0.1387}{2.8 * 47.7}\left(\frac{m3}{ms^{-1} * s}\right) = 0.001039\mathrm{m}^2 \text{ or } 1{,}039\mathrm{mm}^2.$$

The gate inlet, assumed circular and equal to the outlet of the sprue, will have a diameter given by:

$$d_g = \sqrt{\frac{4A_g}{\pi}} = \sqrt{\frac{4*1039}{\pi}} = 36\mathrm{mm}$$

The analysis so far has not taken into consideration, the extra liquid metal that will be needed to feed the casting as will be required by the feeder/riser. This will considerably alter the volume of liquid metal for the casting and hence the gate size. The final gate size can only be obtained by iteration through gate design, feeder design and back to gate design.

2.2.2. The feeder or riser design

The feeder or riser (these terms will be used interchangeably) is a reservoir of liquid metal that provides molten metal to fill the interstices of the growing dendrites as metal solidifies due to liquid-solid shrinkage during solidification. The major requirement of a riser is that it should remain molten long enough till the solidification of the casting is completed. The cooling rate, which determines the rate of solidification, depends on the casting modulus which is the ratio of the volume to the surface

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area of the casting. Castings with small modulus solidify faster than castings with large modulus. The modulus is given by (Beeley, 2001):

$$M_c = \frac{V}{A} = \frac{V}{A} = \frac{LBH}{2LB} = \frac{H}{2} \tag{6}$$

Where, L = Length, B = Breadth and H = Height.

The crusher jaw in the present design has the dimension of 1650 mm x 1085 mm x 110 mm. But due to the teeth profiles and weight reduction grooves on the back side, it can be considered a plate of average thickness of 77.5 mm. The modulus of this plate is half the thickness of the plate or 38.75mm.

In steel castings, the modulus of the riser has to be at least 1.2 times the modulus of the casting to serve as an effective riser. Therefore, modulus of an appropriate riser, would be $M_r = 1.2M_c$ or 46.5 mm. Due to the height of the cope (400 mm), a choice of riser of height to diameter ratio of 1.5 ($H_r = 1.5D_r$) was made. Hence, modulus of riser was obtained as follows:

$$M_r = \frac{\pi R_r^2 H_r}{\left(2\pi R_r H_r + 2\pi R_r^2\right)} = \frac{\pi D_r^2 H_r}{\left(4\pi D_r H + 2\pi D_r^2\right)} = \frac{1.5\pi D_r^3}{8\pi D_r^2} = \frac{1.5D_r}{8} \tag{7}$$

Therefore, for M_r = 46.5 mm, diameter of riser D_r = 248 mm ≈ 250mm, which yields a riser with 250mm diameter and 375mm height, designated 250D_r x 375H_r. This is an appropriate riser to feed the casting; but two parameters have to be checked before the riser's adequacy can be ascertained. These are the feedable weight and the feeding range.

2.2.2.1. *Feedable weight*

Risers or feeders are used to compensate for the solidification shrinkage (decrease in volume resulting during change of state from liquid to solid) for Hadfield steel is taken as 5% (Delta Steel Company, 1980). On the other hand, Feeder efficiency (the ratio of the volume of feed material that a feeder can supply to a casting to the volume of the feeder) depends on the geometry of the feeder and is highest for spherical feeders. However, because spherical feeders are difficult to produce, the most popular feeders are the cylindrical feeders and feeder efficiency here varies with the dimensions, including diameter, D_r to height H_r ratio. Additionally, even when the diameter to height is constant, the feeder efficiency still varies with the diameter; increasing as the diameter increases. The feeder efficiency for a feeder with height $H_r = 1.5D_r$ with D_r = 250mm is approximately 15% (Rashid, 2013). Hence:

$$\eta_r V_r = \alpha\left(V_r + V\ \right) \tag{8}$$

Where, η_r= feeding efficiency, V_r = volume of riser, V_c = volume of casting and α = shrinkage. Substituting the feeding efficiency and shrinkage for our riser and Hadfield steel, we have:

$$\eta_r V_r = \alpha\left(V_r + V_c\right) \tag{9}$$

$$V_c = 2V_r \tag{10}$$

Equation (10) implies that the volume of casting fed by the riser/feeder is equal to twice the volume of the riser. The weight (mass) of the $250D_r$ x $375H_r$ riser is 145 kg; therefore, its feedable weight is 290 kg. Four (4) numbers of this riser will feed 1160 kg and hence this size is considered adequate for the casting with respect to feedable weight.

2.2.2.2. *Feeding range*

A major problem with castings is the presence of defects, particularly, shrinkage cavity and shrinkage porosity resulting from inadequate supply of feed materials. Porosity results if feed materials cannot get to that section of the casting. Bishop and Pellini (1950) reported the investigation of feeding distances of risers after analyzing radiographic results of top risered plates of 2.54 cm and 5.08 cm (1 and 2in) and concluded that a riser placed on top of a plate feeds the riser radius of R_r + 2T (where T is thickness of casting in a sand mould). In other words, the riser feeds twice (2T) from the edge of the riser. In addition, the mould walls cause solidification of 2.5T from the end of the plate. Thus, the riser and the end wall will produce densely fed casting distance of 4.5T from the edge of the riser, made up of 2T riser-zone and 2.5T end-zone or Rr + 4.5T from centre of riser to end of casting. The experiment by Bishop and Pellini (1950) was defined for plates with W/T $\geq$ 3, that is width to thickness ratio.

Feeding distance studies was further extended by Myskoski et al. (1953) for bars of 5.08 cm to 15.2 cm (2 to 6 in) cast horizontally and vertically and investigated plates in the same range but for plates of W/T = 5 and with chills. These experiments resulted in feeding distance for bars of $9.56\sqrt{T} + T$ cm ($6\sqrt{T} + T$ in) and 4.5T + T for plates with chill. The Steel Founders Society of America, SFSA also investigated feeding distances and produced rules that more or less corroborated the results of Bishop and Pellini (1950) and SFSA published casting rules used in most foundry operations (SFSA, 1973). New casting distance rules have been developed by Shouzhu et al. (2002), which is based on a correlation of Niyama Criterion and radiographic casting soundness and provides normalized graphs and monographs that give the distance of sound casting of the riser and the end zone (SFSA, 2001; Shouzhu et al., 2002). This new rules covers the range of W/T = 1 to 7 when feeding distances by riser and end zone stop depending on W/T and hence become constant. In our current design, we took feeding distances from the nomograph of RZL/T and EZL/T against W/T shown in figure 3. RZL represents riser feeding length while EZL represents end zone feeding length (Shouzhu et al., 2002).

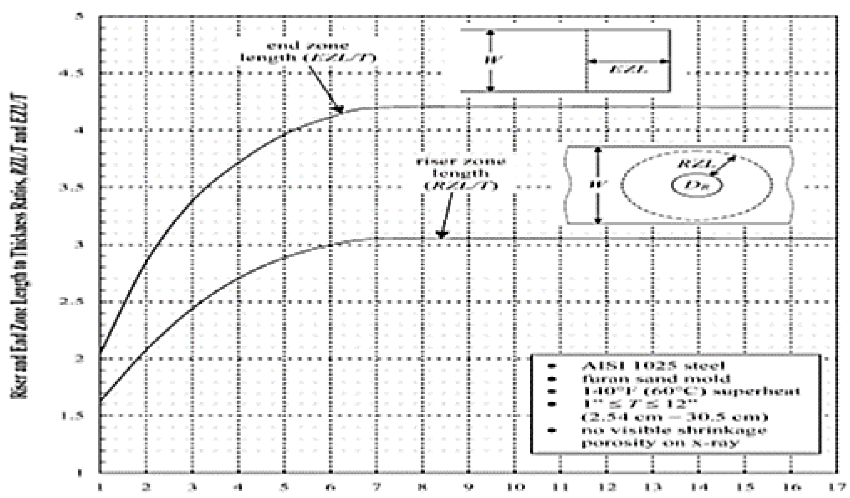

Figure 3: Riser and end zone feeding distances (Figure reproduced from Shouzhu et al., 2002)

The first consideration assumed that the casting can be fed by top risering though by the feature of the casting, this is not a plausible option due to the teeth profiles and the back grooves. However, if this was possible, 4 risers would have fed the casting with the following feeding distances as shown in Figure 4. The ratio, W/T, i.e. width over thickness is 1,058/77.5 or 14, which falls within the constant feeding distance region where RZL/T = 3.05 and EZL/T = 4.2 from Figure 3. Consequently, feeding distances RZL = 3.05x77.5 = 236mm and EZL = 4.2x77.5 = 325mm, by making RZL and EZL the subjects of the equation. The casting will be fully fed if it can be top risered because RZL + EZL = 236 + 325 = 561mm, which is more than half the length of the casting. The circles of influence are shown in Figure 4 and extend to the edge of the casting.

However, the jaw teeth and back recesses preclude the use of top risering. Hence, to achieve directional flow, the risering can only be along the teeth axis, resulting in side but axial risering. With this situation, the four (4) risers are placed two (2) at both ends, which will affect the end zone effect. The effects of placing the risers at the axial ends are presented in Figure 5.

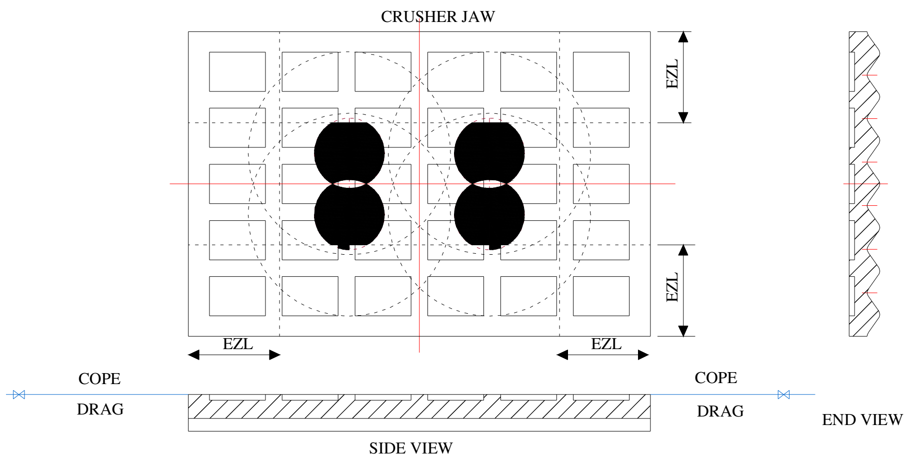

Figure 4: Crusher jaw with 4 top risers

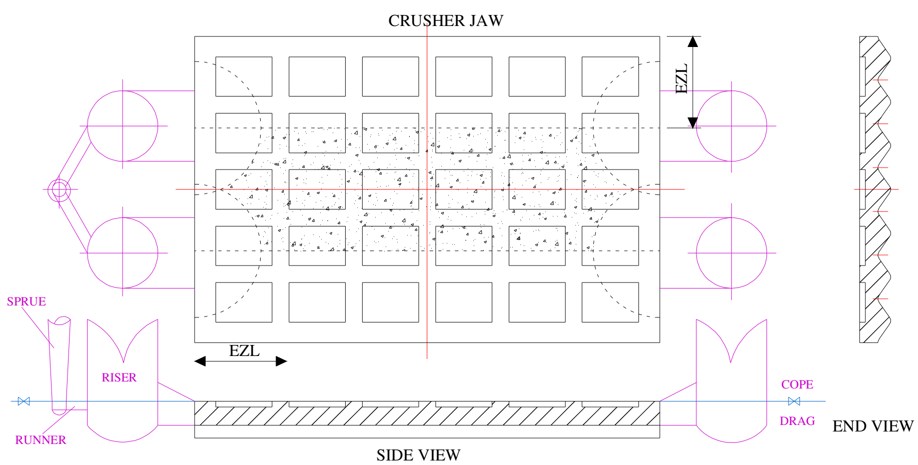

Figure 5: Crusher jaw with 4 side risers

In the side riser of the casting, the EZL remains the same as in the top risering but the RZL or portion fed by the riser is very small from the risering graph for side risers (not provided) according to the new feeding distance rules. This leaves a large central section that will be prone to shrinkage porosity. Apart from that, the risers are feeding areas that should be covered by the end zone effects, hence further adjustment on the position of the risers or some redesign was necessary.

The main problem left to be solved is how to advance the riser feeding distance to cover the unfed central zone (dotted central section). Two modifications were introduced to achieve a possible shift in the feeding range. The first was to reduce the wasted feeding range of the risers that were covering the end zone ranges by bringing the risers close to each other (Figure 6). Putting the risers together coverts the risers effectively from cylindrical risers to oval risers. The concentrated effect pushes the RZL further into the casting. The second was the used of drag chill of size 2/3T x 2/3T across the width of the casting along the centre. This will further extend the riser feeding zone until the casting is fully fed. Figure 6 represents the final riser design and is an oval riser which is effectively two combined cylindrical risers. The dotted lines show the riser, the EZL and the RZL.

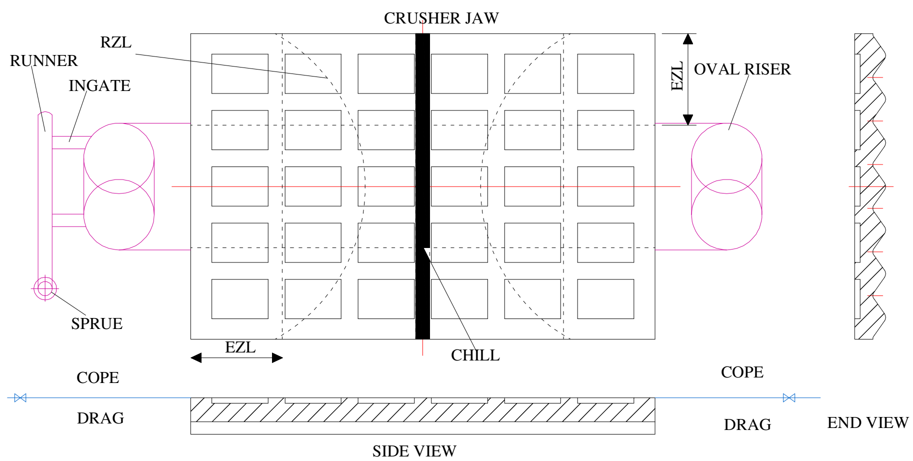

Figure 6: Final riser design as oval riser

2.2.2.3. ***Neck design***

The use of side riser introduced the problem of how to design the connection between the casting and the riser. Though the final design is for oval riser, the connection or neck will be designed based on the cylindrical riser, recognizing that the oval riser is actually a double cylindrical riser. To achieve directional flow from the riser to the casting, the modulus of this neck has to be between the modulus of the casting and that of the riser (Sutaria et al, 2011). The modulus of the riser is $M_r = 1.2M_{c,}$ therefore the modulus of the neck should be $M_n = 1.1M_{c.}$ It is necessary to slope the neck from the riser to the casting to taper the modulus for achieving the directional flow. The neck thickness is the same as the plate thickness at the entry into the casting while a ratio of neck thickness at riser, T_{nr}, to neck thickness at casting T_{nc} of 1.2 is assumed, i.e. $T_{nr} = 1.2T_{nc}$ (Figure 7). Let the width of the neck, W, be equal to the diameter of the riser, D_r, and the distance between riser and casting be L, then the dimensions of the neck is determined from the modulus of the neck. The modulus of the neck is:

$$M_n = \frac{(T + 1.2T)LW_n / 2}{(T + 1.2T)2L/2 + TW_n + 1.2TW_n} = \frac{LW_n}{2(L + W_n)} \tag{11}$$

Equation 11 indicates that the modulus of the neck is a function of the length, L and width, W, and thickness T. The width of the neck is the same as the width of the riser, hence, the modulus will be determined by the length of the neck. In this case, the width is equal to the riser diameter, (250 mm) and the modulus, $M_n = 1.1M_c = 42.625$ mm. The length is determined from equation 10 as shown below:

$$M_n = \frac{LW}{2(L+W)} = \frac{250L}{2(L+250)} = 42.625$$

Therefore, calculating for L, we have.   L = 129.36 mm = 130mm

The length to keep the riser neck hot throughout the solidification period is 130 mm. The neck of the oval riser is double the design just described for a cylindrical riser.

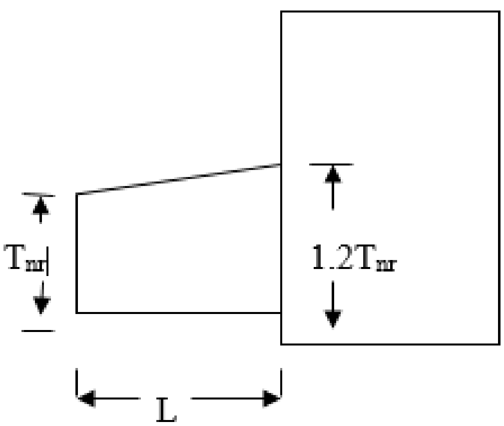

Figure 7: Riser neck design

2.2.2.4. ***Modified gate design***

The risers were still considered as cylindrical risers for the purpose of this design since the oval risers were two cylindrical risers combined. The riser size was $250D_r$ x $375H_r$; but due to available mould box for this casting, the actual height of riser was 400mm. The volume of a riser was 0.0196 m^3 and for the 4 risers, 0.0785 m^3. The original volume of the casting was 0.1387 m^3, which when added to the volume of risers yielded 0.2172m^3 as the total volume to be cast. The area of gate from Equation (5) based on the total volume cast is:

$$A_g = \frac{V_c}{\upsilon_g t_s} = 1626 \text{ mm}^2.$$

Thus, the gate inlet, assumed circular and equal to the outlet of the sprue, will have a diameter given by:

$$d_g = \sqrt{\frac{4A_g}{\pi}} = \, = 45.5 \text{ mm}$$

It should be noted that the area of the gate as determined from Equation (5) is actually the area at the base of the down-sprue considered to be equal to the area of the gate. In steel casting, the gating system is best designed unpressurised, that is, the area of the sprue is less than the area of the runner, which is in turn, less than the area of the ingates. Hence, the ratio, $A_s : S_R : A_g = 1 : 1.2 : 1.5$.

A_s is area of sprue, A_R is area of runner and A_g is area of ingates is in use.

If the risers were placed as in Figure 4, the gating would have been made up of only sprue and runners, so the area of the runners will be, $S_R = 1.2A_s$. The area of sprue determined for the full casting using Equation 5 is 1626 mm^2; therefore, combined area of runners is 1.2 x 1626 or 1951 mm^2. For ease of moulding, rectangular or trapezoidal runners would be used. There would be two runners; hence, each runner has area = 975mm^2. The size of 32mm x 30mm rectangular runner or 35/30mm x 30mm trapezoidal runner; 30mm was assumed as the thickness of the runner. . For the oval riser, the gating will consist of sprue, runner and ingates as shown in Figure 5. There will be one runner of cross-sectional area 1951 mm^2 and if the width of the runner is assumed to be the same as the diameter of the sprue choke, then the depth will be 43 mm, i.e. 45.4 mm x 43 mm runner. The combined area of the ingates was $1.5A_s$, which was 2,439 mm^2 and the size of each of the two ingates were 40 mm x 30 mm.

3. RESULTS AND DISCUSSION

The crusher jaw was cast with the riser and runner designed above and the outcomes are shown in Plate 1 and 2. Plate 1 shows the fully formed teeth indicating that the gating was adequate; without short runs and cold shuts, which are evidence of poor gating.

Plate 1: Cast crusher jaw with fully formed teeth

Plate 1 also shows and end view which was the point of riser attached. The expected defect if risering was inadequate is a shrinkage cavity but there was no shrinkage cavity indicating risering adequacy. On the other hand, Plate 2 showed the back-recessed part of the casting. It showed the casting before cleaning. This portion was cast faced-up and there are burnt mould sand mostly at recess corners. These are regions of high temperature concentration, which is expected in sharp corners; also indication of inadequate fillets at the corners of the recesses.

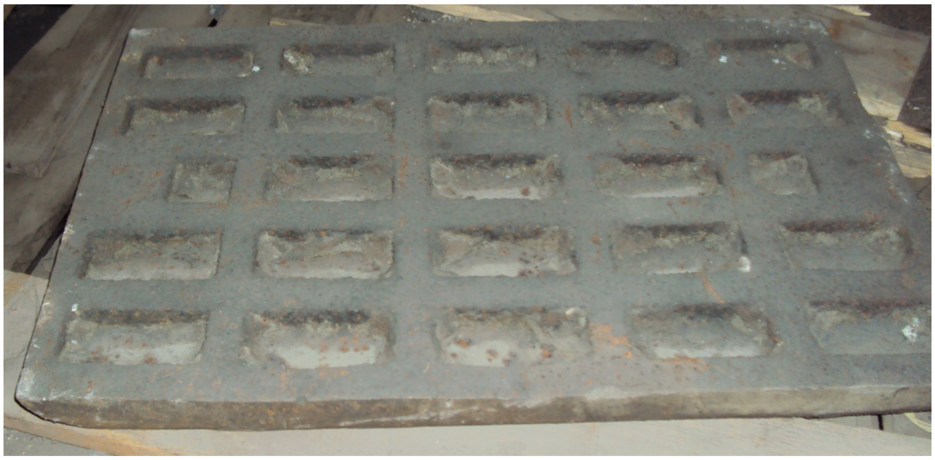

Plate 2: Cast Crusher jaw with back recesses

4. CONCLUSION

The design was successful because the casting was made with the specified design parameters and on casting, there were no visible defects that could be associated with design errors. The casting was without short-run or cold-shut and all the teeth and recesses were well formed. The risers provided proper feeding because there was no shrinkage cavities extending into the point of attachment to the casting. After proper heat treatment, the crusher jaw was installed in the jaw crusher and was successfully put to use.

5. ACKNOWLEDGMENT

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6. CONFLICT OF INTEREST

There is no conflict of interest associated with this work..

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