Optimal Feeder Design of Pressure Vessel from Gunmetal Using Investment Casting – A Case Study

Enil Kansagra, Parth Shah, Kishan Fuse

Abstract—**Investment casting, also known as precision casting or lost-wax casting is an industrial method to produce high dimensional accuracy castings. This method uses an expendable-mould process to cast complex shapes with superior surface qualities. Ferrous and non-ferrous metals, both can be cast by this process. Even castings having thin sections (0.4mm) are being cast using this method. But this process may sometime produce casting having defects such as gas porosity, shrinkage cavity, cold shut, burrs, sand cut, pinhole, blowhole, insufficient pouring, etc. Porosity is the most common defect encountered in the castings. To achieve excellent surface qualities with minimum or no castings defects, a proper feeding system has to be designed. It is a critical step for design engineers to design feeder, choose the optimum location of feeder and number of feeders. Traditional manual methods used to design a feeder may involve a large number of trials which in turn may reduce profits, percentage yield or other resources. To decrease the product development time, one such modern approach is to use computerised casting simulation software. In this software, a large number of geometrical changes can be made to feeding system instantly and at the same time, tested for its optimality. In this paper, a step by step guide to design feeding system for a part of pressure vessel of 'Elbow' shape (Bronze: BS 1400 – Gr. LG2) is presented. Modelling of feeder is done using Siemens NX software and simulation is done using SoftCAST software. All the design parameters are set in such a way that all the hotspots, shrinkage cavities and gas porosities occur in feeder and not in casting. This modern technique has shown significant quality improvement than the traditional methods.**

Keywords—**Optimal design of feeding system, Modulus method, Simulation, Bronze: BS 1400 LG2 (Gunmetal), Investment casting.**

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I. Introduction

DEMAND of designs, cost incurred and feasibility in manufacturing of product will determine which manufacturing processes are convenient while choosing a product to manufacture. Investment casting process employs procedures that yield components with high precision and accuracy which reduces wastage of energy, manpower, raw materials and further machining. It is the only process which enables production of very intricate parts and is capable of producing components in repetitions with high accuracy and integrity in a variety of metals.

Solidification stage is the most crucial stage of the casting procedure. Produced casting will have superior quality with minimum defects when properly solidified. Solidification of casting takes place from cavity wall towards the centre. Also, thicker sections take longer solidification time than thin sections. Evolution of hotspots during solidification causes defects. Here, feeding system plays an important role in maintaining the qualities of casting products, especially in the case of pressure vessels, where there should be zero porosity defects or any other shrinkage cavities. The alloy shrinks in volume as it cools down to liquidus temperature and then eventually solidifies with volume contraction. Hence the feeders are provided near the hotspots which in turn supply molten metal to compensate for volumetric contraction. Also, an appropriate feeding system will implement directional solidification of casting.

The metal in this case study is "Bronze: BS 1400 LG2" used to make pressure vessel. LG2 Leaded Gunmetal Bronze exhibits certain properties such as machinability, medium strength, pressure tightness, exceptional resistance to superheated steam, corrosion resistance to seawater and brine. Due to these properties, it is suitable for pressure-tight pump and valve components, fittings and general engineering components.

In this case study, The Chvorinov's rule is used to design the feeding system; which was later elaborated by Wlodawer, known as modulus method. Modulus of any component can be defined as the ratio of volume to the surface area of that component.

$$M = {}^{V}\!/_{CS}$$

Where, M = modulus of casting element
V = volume of casting element
CS = cooling surface area of casting element

This ratio is easily calculated for castings with simple geometry. But when it is required to design complicated geometry, it becomes difficult to calculate. To eliminate this difficulty, the complicated geometry is divided into simpler parts or sections and then the modulus is calculated for each section. While the calculation of surface area, only cooling surface area is considered. While designing feeder, a thumb rule is followed i.e. the feeder should solidify after the casting has solidified so as to compensate for volumetric contractions.

Developing gating system for any component consumes a huge amount of time, cost and manpower for manual trials and for any new component, the existing systems may not be efficient. Hence many methods are used to determine the dimensions of feeding system elements such as Caine's method, Bishops method, Chvorinov's rule, Wlodawer's method etc. The designed components are evaluated in casting simulation software. 3D model of the casting along with its feeding system is created using Siemens NX software and the heat flow simulation is done using SoftCAST software.

II. Literature Review

Existing literature showed that many types of research and experiments have been done for designing optimal feeding system so as to remove casting defects. Prediction of microstructure and cavities can be easily made using simulation software [1]. They designed the feeding system based on the Chvorinov's rule and porosity-Niyama Criterion relationship. The turbulence effect on four different feeding methods for aluminium alloy 2L99 investment casting showed that controlled bottom filling with filter was a superior method [2]. The previous designs to manufacture exhaust manifold by investment casting produced poor quality and defective castings [3]. They corrected this problem by using ProCAST simulation software to obtain optimal design. They were even successful in increasing casting yield. Understanding the solidification process and suggesting for directional solidification of castings [4]. Shrinkage, porosity and other defects occurred due to incomplete filling in varying thickness. With the help of AutoCAST X software, they were able to locate and design feeder optimally. The use of casting simulation software saves time, cost and resources and even solidification simulation can overcome the difficulties of manual modifications [5]. They checked the existing gating system for cast iron and developed a new optimal design for defect-free casting. Presentation of a step by step procedure for designing feeding system by taking spacer as a case study [6]. The metal they used is CA15 and the manufacturing process is investment casting. They designed the feeder based on heat transfer criteria and feed volume criteria. 90% of the defects are due to improper feeding system [7]. They studied the existing gating design in sand casting and made some changes in it using AutoCAST-X_1 casting simulation software. These simulated results were then compared with experimental results and it resulted in 30% reduction in rejection of casting. Proposal of a new method based on geometric reasoning method (GRM) and fruit fly optimization algorithm (FOA) in CAD [8]. GRM is used to locate every hotspot and then FOA is used to design geometry of riser. These methods were effective in reducing time and cost of the production cycle.

III. Research Methodology

The case study is performed in three stages i.e. calculation of modulus, design of feeder as per calculated modulus and heat flow simulation using SoftCAST software. Investment casting is used as manufacturing process and the metal being cast is Bronze: BS 1400 LG2. The mould material is silica sand. The chemical composition of selected casting metal is shown in Table I.

Steps for Design optimization of feeder:

1. Draw a 3D model of the item to be cast
2. Point out thick sections in the casting
3. Calculate the modulus of these thick sections
4. Determine the number of feeders
5. Calculate dimensions of feeder on the basis of modulus
6. Calculate dimensions of feeder neck on the basis of modulus
7. Check for heat flow by simulation

3D model of Elbow is prepared using Siemens NX software and is then checked for heat flow using SoftCAST software; which locates all the hotspots. A feeder is placed at the location of hotspots. Depending on this location, dimensions of feeder and feeder neck is designed. Simulation also helps in many ways such as:

1. It helps to locate regions having highest solidification time
2. It identifies all the hotspots in the casting
3. It helps to check directional solidification of the casting
4. It helps in locating feeder and calculating its dimensions
5. It helps to locate other defects like shrinkage cavities, porosities etc.

IV. Case Study

This case study shows the different trials made while designing feeding system for Elbow. Using different software for designing purpose is helpful to minimize wastage of resources such as energy, material, manpower, time etc. If any defect is found, it is better to rectify in a software than to rectify in a production process. 3D model of Elbow is made as per the 2D specifications given in the drawing. This 3D model is then used for simulation purpose. Fig. 1 shows the 3D model of 90° Elbow.

TABLE I
CHEMICAL COMPOSITION OF BRONZE: BS 1400 LG2

	Cu%	Pb%	Sn%	Zn%	Al%	P%	Ni%	Si%
MIN	83.00	4.00	4.00	4.00	-	-	-	-
MAX	87.00	6.00	6.00	6.00	0.01	0.10	2.00	0.01

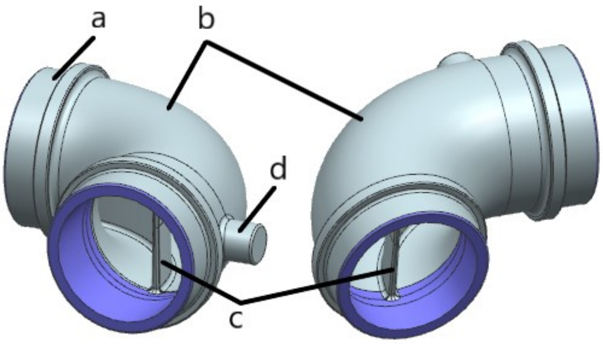
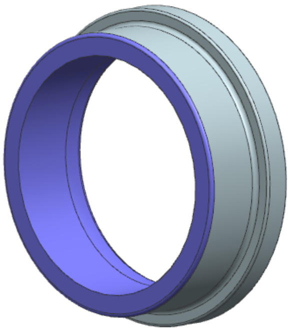


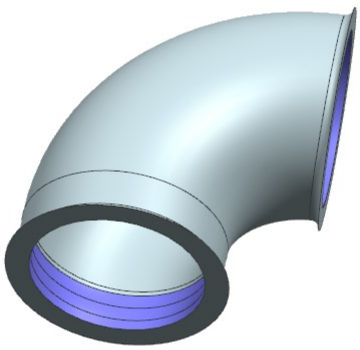
Fig. 1. 3D model of Elbow

As it is a complicated shape, this casting is subdivided into 4 sections as shown in fig. 2:

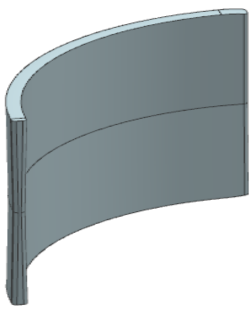
a) Ring (2 extreme rings):



b) Tube:



c) Baffle:



d) Boss:

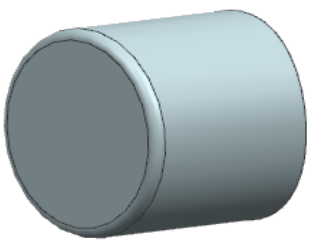


Fig. 2. Subdivided sections of Elbow

Solidification time depends upon the modulus of the respective section. Modulus of the different section is calculated in table II.

TABLE II
MODULUS OF DIFFERENT SECTIONS

Section	Volume (v) (mm^3)	Cooling surface area (cs) (mm^2)	Modulus (v/cs)
a	1,47,870.84	24,456.78	6.04
b	4,21,868.41	69,816.41	6.04
c	77,981.20	33,768.57	2.31
d	18,006.76	3,104.58	5.80

NOTE: the value of volume and the cooling surface area is measured using Siemens NX software.

The section having maximum modulus is the region with highest solidification time and will be the last region to freeze. It is observed that maximum modulus (M_C) is 6.04 which found at section 1 and 2. Hence this region is appropriate for installing a feeder to prevent shrinkage or porosity defect. Also to avoid defects, following ratio is followed [6]:

$$M_C : M_N : M_F = 1 : 1.1 : 1.2$$

Here M_C = modulus of casting
M_N = modulus of feeder neck
M_F = modulus of feeder

A. *Design of Feeder*

Rectangular bar shape is chosen for feeder as shown in fig. 3(a) and the feeder neck has a tapered geometry as shown in fig. 3(b). Taper creates a pressurised feeding system and also helps in maintaining temperature gradient throughout the casting. Since the junction between the casting and the neck has a narrow area, it becomes easier to cut-off feeders from the casting.

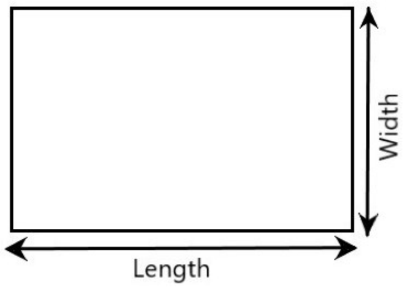


Fig. 3(a). Feeder with rectangular cross section

Modulus of feeder (M_f) = 1.2*M_c = 1.2*6.04 = 7.25
Dimension of feeder = 4*7.25 = 29mm

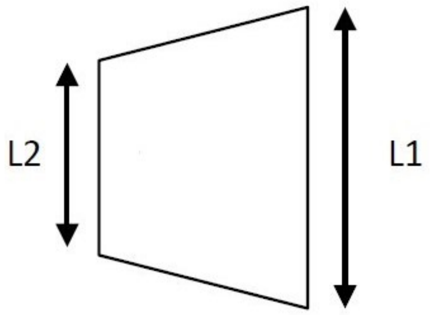


Fig. 3(b). Feeder neck with taper cross section

Modulus of neck (M_n) = 1.1*M_c = 1.1*6.04 = 6.64
Dimension of neck = 4*6.64 = 26.56mm

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Based on these calculated dimensions, few trials are shown by selecting different dimensional values of feeder and feeder neck. The whole feeding system is given a height of 5.5 inches so as to increase the pressure head.

- Trial 1: the dimension of feeder is taken above its calculated value and the dimension of neck is taken below its calculated value.
  Neck dimensions: L_1 = 32mm
  L_2 = 23mm
  H = 50mm
  Pouring basin cup diameter = 50mm
  Height = 50mm
  Rectangular feeder = 30x30mm (length x width)
  Taper angle = 5°

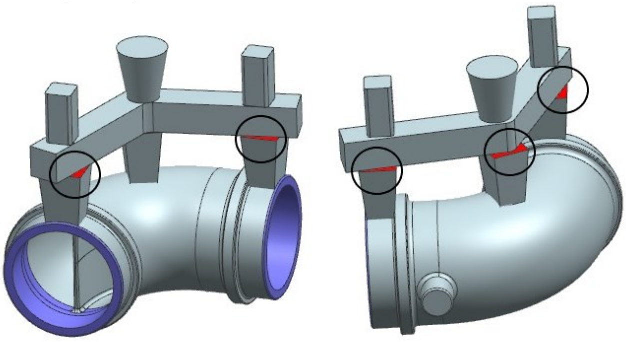
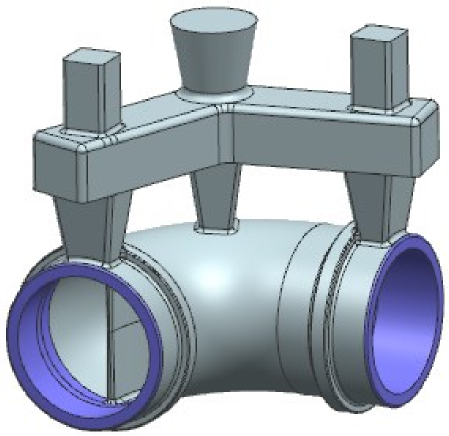


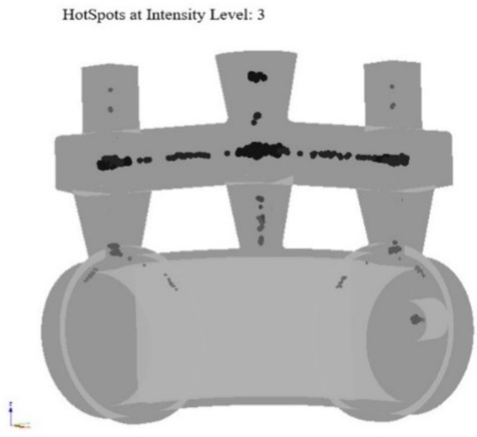
Fig. 4. Modelling result with trial 1

The area of feeder is less than the area of projected trapezoidal neck as shown by circles in fig. 4. Due to this, there is improper contact between feeder and neck which will lead to difficulty in ceramic coating over the wax pattern. Also as the neck region becomes thicker than the feeder, a reverse temperature gradient is formed and it causes hotspots to appear in the casting. So to avoid this, a feeder having a standard rectangular cross section as 50x40mm (length x width) is used.

- Trial 2: The dimension of neck is taken below its calculated value.
  Neck dimensions: L_1 = 32mm
  L_2 = 23mm
  H = 50mm
  Pouring basin cup diameter = 50mm
  Height = 50mm
  Rectangular feeder = 50x40mm
  Taper angle = 5°



(a)

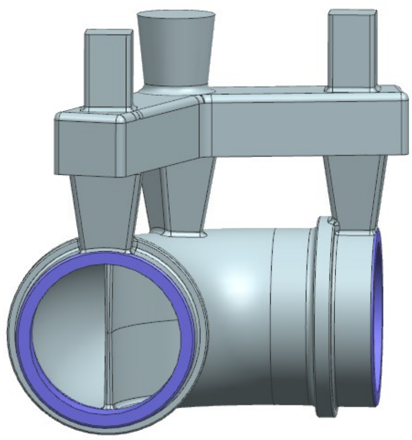


(b)

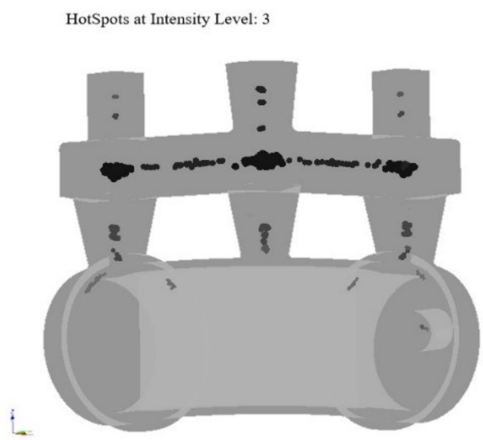
Fig. 5. (a) Modelling result with trial 2 and (b) Simulation result with trial 2

It is clearly seen in fig. 5(b) that there are hotspots present in the casting. Hence the dimension (32x23mm) of neck is inappropriate and has to be changed.

- Trial 3: The dimension of neck is taken close to calculated value.
  Neck dimensions: L_1 = 32mm
  L_2 = 26mm
  H = 50mm
  Pouring basin cup diameter = 50mm
  Height = 50mm
  Rectangular feeder = 50x40mm
  Taper angle = 5°



(a)



(b)

Fig. 6. (a) Modelling result with trial 3 and (b) Simulation result with trial 3

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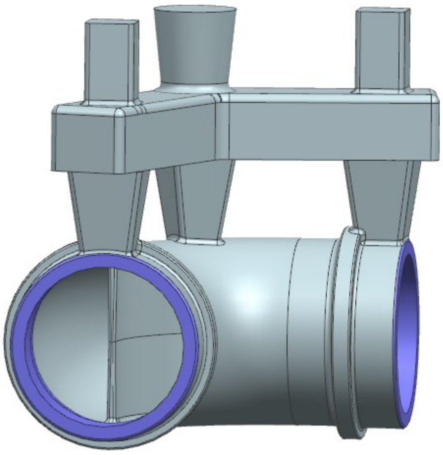
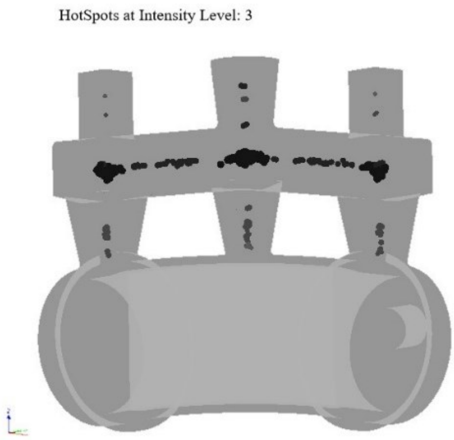
It can be seen from the fig. 6(b) that the hotspots are moving towards the feeder. But a small amount of hotspots is still present in the casting. Hence even the dimension (32x26mm) of neck which is very near to calculated value (26.56mm) is inappropriate and has to be increased.

- Trial 4: The dimension of neck is taken greater than the calculated value.
  Neck dimensions: $L_1 = 32$mm
  $L_2 = 29$mm
  H = 50mm
  Pouring basin cup diameter = 50mm
  Height = 50mm
  Rectangular feeder = 50x40mm
  Taper angle = 5°



(a)



(b)

Fig. 7. (a) Modelling result with trial 4 and (b) Simulation result with trial 4

It can be seen from the fig. 7(b) that there are no hotspots present in the casting. Hence the optimal design of feeder is achieved which contains no hotspots. The results obtained in different simulation trials is summarised in table III.

V. Conclusion

1. Trial & error approach is employed to design a hotspot free casting.
2. In our case, the calculated value of neck dimension is 26.56mm. Even the neck dimension = 26mm gave hotspots in the castings. Therefore, the value of all dimensions should be greater than the calculated value.
3. Sometimes the actual value of the dimension is taken large than the calculated value so as to make a proper feasible geometry like in the case of feeder.
4. Solidification simulation helped in developing an optimal feeding system which in turn produced a sound casting without wasting resources.

Thick sections and junctions in casting are often prone to shrinkage cavities. This will lead to poor casting strength and ultimately failure. Proper location and design of feeding system have benefited in overcoming casting defects and fulfilment of directional solidification towards feeder. Simulation using SoftCAST software was a great approach towards minimizing the defects and produce sound casting.

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TABLE III
Summary of Different Simulation Trials

Parameters	Neck Dimensions (mm)			Feeder Dimensions (length x width) (mm)	Result of Simulation	Constant values: Pouring basin cup: diameter = 50mm height = 50mm Taper angle = 5°
Trials	L_1	L_2	H			
Trial - 1	32	23	50	30x30	Infeasible geometry of feeder	
Trial - 2	32	23	50	50x40	Hotspots present in the casting	
Trial - 3	32	26	50	50x40	Fewer hotspots present in the casting	
Trial - 4	32	29	50	50x40	No hotspots present in the casting	

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