

Warpage in casting: A Review

Prachi K. Taweale¹, Laukik P. Raut²

¹Student M.Tech CAD/CAM, GHRCE Nagpur- 440016, India, p.taweale@gmail.com

²Assistant professor, Mechanical Department, GHRCE Nagpur- 440016, India, rautlaukik@gmail.com

Abstract— Foundry industries in developing countries suffer from poor quality and productivity due to involvement of number of process parameter. Even in completely controlled process, defect in casting are observed and hence casting process is also known as process of uncertainty which challenges explanation about the cause of casting defects. In order to reduce warpage defects and problem related to warpage defects, the study is aimed in this paper. Many products are made by using casting process as it is economical and has the ability to produce intricate shapes. So far, casting defect analysis has been carried out using techniques like finite element method and modulus method to reduce defects. . Casting software can optimize the virtual castings so that real castings can be produced 'right first time and every time'.

Keywords— Sand casting, warpage, solidification, software, simulation.

I. INTRODUCTION

Casting is a manufacturing process by which a liquid material is usually poured into a mold, which contains a hollow cavity of the desired shape, and then allowed to solidify. The solidified part is also known as a casting, which is ejected or broken out of the mold to complete the process. Casting materials are usually metals or various cold setting materials that cure after mixing two or more components together such as epoxy or clay. Casting is generally used for making intricate shapes. In a casting process, the material is first heated to completely melt and then poured into a cavity of the mold. As soon as the molten metal is in the mold, it begins to cool. When the temperature drops below the freezing point (melting point) of the material, solidification starts. Solidification involves a change of phase of the material and differs depending on whether the material is a pure element or an alloy. A pure metal solidifies at a constant temperature, which is its melting point (freezing point). The phenomenon of casting solidification, accompanies by volumetric contraction, leads to several major defects in casting including shrinkage cracks and distortion. The location and extent of shrinkage can be predicted by identifying regions of high temperature and low gradients (short feeding distance). Unfortunately, castings can be of complex shapes, and the heat transfer from all faces of the mold may not be uniform. Other factors, such as air gap formation at the metal-mold interface, convection in liquid metal, application of feed aids, presence of cores, gating system design and pouring parameters also affect the of shrinkage. In recent years, computer simulation of casting solidification has gained much ground, owing to the

constant and painstaking efforts of researchers to make such software tools more reliable and easy to use.

II. LITERATURE REVIEW

A. Sand casting

Sand casting, [7] the most widely used casting process, utilizes expendable sand molds to form complex metal parts that can be made of nearly any alloy. The sand casting process involves the use of furnace, metal, pattern and sand mold. The metal is melted in the furnace and then ladled and poured into the cavity of the sand mold, which is formed by the pattern. The sand mold separates along a parting line and the solidified casting can be removed.

Basically sand casting process consists of:

- 1) Placing a pattern (having the shape of the desired casting) in sand to make an imprint;
- 2) Incorporating a gating system;
- 3) Removing the pattern and filling the mold cavity with the molten metal;
- 4) Allowing the metal to cool until it solidifies;
- 5) Breaking away the sand mold;
- 6) Removing the casting [7].

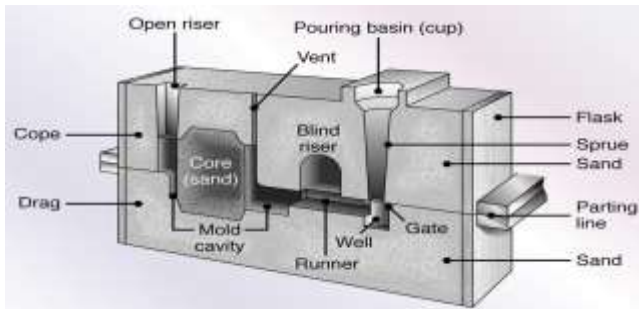


Figure 1. Schematic illustration of sand mold

The typical sand casting process design consists of the following steps.

a. Sand Selection

Several factors are important in the selection of sand for molds, and it involves certain tradeoffs with respect to properties. Although fine-grained sand enhances mold strength, the fine grains also lower mold permeability. Good permeability of molds and cores allows gases and steam evolved during the casting to escape easily. The mold has should have good collapsibility to allow for the casting to shrink while cooling and, thus, to avoid defects in the casting, such as hot tearing and cracking. [7]

b. Pattern design

The pattern is a replica of the object to be cast, used to prepare the cavity into which molten material will be poured during the casting process.

The mold is made by packing some readily formed aggregate material, such as molding sand, around the pattern. When the pattern is withdrawn, its imprint provides the mold cavity, which is ultimately filled with metal to become the casting. [7] During the design process of pattern, some considerations should be taken. For example, the pattern needs to incorporate contraction allowances, which are suitable allowances for shrinkage. And also it needs to incorporate suitable allowances for draft. If the casting is to be hollow, as in the case of pipe fittings, additional patterns, referred to as cores, are used to form these cavities.

c. Parting line

Parting line is the line or plane separating the upper and the lower halves of molds. In general, the parting line should be along a flat plane rather than be contoured. Whenever possible, the parting line should be at the corners or edges of castings rather than on flat surfaces in the middle of the casting. It should be placed as low as possible for less dense metals and located at around mid-height for denser metals. [7]

d. Core design

Cores are forms, usually made of sand, which are placed into a mold cavity to form the interior surfaces of castings. Thus the

void space between the core and mold-cavity surface is what eventually the casting becomes. [7]

e. Gating/riser system design

The preparation of molten metal for casting is referred to simply as melting. Melting is usually done in a specifically designated area of the foundry, and the molten metal is transferred to the pouring area where the molds are filled. After pouring metal, it will flow through the gating system until the cavity is fully filled. Then the metal begins to cool and solidify with the occurrence of shrinkage. Riser system is designed to compensate such shrinkage. Gating/riser system has great effects on the final quality of casting. A foundry can produce the best quality molds, cores and molten aluminum and still end up with a poor quality casting by using poorly designed gating and riser systems. So how to design a satisfied gating/riser system is very important.

The main objective of a gating system is to lead clean molten metal poured from ladle to the casting cavity, ensuring smooth, uniform and complete filling. Clean metal implies preventing the entry of slag and inclusions into the mould cavity, and minimizing surface turbulence. Smooth filling implies minimizing bulk turbulence. Uniform filling implies that all portions of the casting fill in a controlled manner, usually at the same time. Complete filling implies leading molten metal to thin and end sections with minimum resistance.

There are many factors affecting the design of an ideal gating system. For example, the gating system should be designed to allow the molten metal flow through with the least amount of turbulence. It is a better design of the gating system that it can be removed easily from the casting after filling. The gating system should be designed in such a way to promote the directional solidification. After meeting other requirements of gating system, it will also need lower yield. [7]

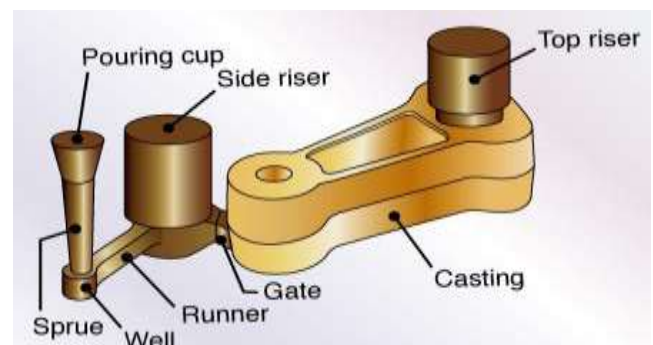


Figure 2. Typical gating/riser system

i. Sprue

It is a circular cross-section minimizing turbulence and heat loss and its area is quantified from gating ratio. The area of the

sprue top should be calculated using mass and energy balance equations, to prevent flow separation in the sprue.

$$A1 \sqrt{H1} = A2 \sqrt{H2}$$

Where, $H1$ and $H2$ are the metallostatic pressure head at the top and bottom of the sprue, respectively; $A1$ and $A2$ being the respective cross-sectional areas.

ii. Sprue well

It is designed to restrict the free fall of molten metal by directing it in a right angle towards the runner. It aids in reducing turbulence and air aspiration.

iii. Runner

Mainly slows down the molten metal that speeds during the free fall from sprue to the ingate. The cross section of runner should be greater than the sprue exit, it is recommended that the runner cross section area must be lowered after each ingate connection to ensure smooth flow.

iv. Ingate

It directs the molten metal from the gating system to the mold cavity. It is recommended that ingate should be designed to reduce the metal velocity. [10]

f. Optimal Filling time

Filling time is very crucial in casting as it decides the final quality of product. A slow fill gives casting defects while a fast fill can lead to solid and gaseous inclusions.

The ideal filling time is a function of cast metal, weight, minimum section thickness and temperature and can be expressed as,

$$t_f = k_0(k_f L_f/1000)(k_s + k_t t/20)(k_w W)^P$$

Where t_f is the casting time, W is the weight in kg, t is the section thickness in mm and L_f is the fluidity length in mm, whereas k_0 , k_f , k_s , k_t , k_w are all coefficients. The value of these coefficients can be set to achieve a perfect metal process combination in specific castings.

The velocity of molten metal plays crucial role in deciding the optimal filling time. The velocity usually varies within the gating channels and the mold cavity. It depends majorly on gating ratio.

Gating ratio : Gating ratio is the ratio of sprue area to total runner area to total gating area. ($A_s:A_r:A_g$)

Where, A_s , A_r , A_g are the cross-sectional areas of sprue exit, runner(s) and ingate(s). If multiple runners and ingates are present, the total area of all runners, or all ingates, respectively must be considered. A converging diverging system, where the ingate area is more than the sprue exit area, is to be preferred. This ensures that the metal slows down thereby reducing turbulence-related problems. [10]

g. Assessment of gating design

Different combinations of gating system designs and mold filling are carried out to completely eliminate filling defects. A gating system can be assessed using the following criteria,

- ii **Mold filling time :** The actual mold filling time must be close to the optimal filling time of the gating system. This can be expressed as,

$$CG1 = 1 - (t_f \text{ actual} - t_f \text{ optimal}) / t_f \text{ optimal}$$

If a casting is found to have filling-related defects at the optimal filling time, but is defect-free at some other filling time, then the empirical equation for optimal filling time may be corrected for the particular combination of geometry, metal and process.

- iii **Ingate velocity :** The velocity of molten metal emerging from the ingate must be as low as possible to minimize turbulence. It can be expressed as,

$$CG2 = 1 - (V_{\text{ingate}} / v_{\text{critical}})$$

Where, V_{critical} is the recommended limit of velocity depending on the metal: about 1 m/s for iron, and 0.5 m/s for aluminum.

- iiii **Gating yield :** The volume of the gating system must be minimized to increase the yield. The criterion is given by

$$CG4 = N_c v_c / (N_c v_c + v_g)$$

Where, N_c is number of casting cavities per mould, v_c is the volume of each cavity, and v_g is the volume of the common gating system for all the cavities in the mould.

- iv **Fettling :** The ingate size must be small in comparison to the connected part of casting to avoid breakage and cracks. When several ingates are present, one that is most likely to cause damage determines the criteria assessment value.

$$CG5 = \min_i (1 - (t_{gi} / t_{ci}))$$

Where, t_{gi} is the thickness of ingate i and t_{ci} is the thickness of the connected portion of casting.

h. Validation of gating design

The gating design can be validated using the following techniques,

- i **Shop floor trials :** Samples are produced using the actual materials and process that would be finally employed. These are observed for surface, sub-surface and internal quality and destructive and non-destructive testing methods.
- ii **High speed radiography :** The mold filling phenomenon is recorded using a high speed x-ray camera and observed of any defects.

- iii **Open mold** : In this a portion of cope above casting cavity is cut and a flow of molten metal stream from ingate and gradual filling of the mold is recorded.
- iv **Water in transparent mold** : Flow of water in a transparent mold is a very useful tool. Addition of color marker, oil droplets can help in better visualization and recording velocities in different sections.[10]

i. Solidification

After molten metal is poured into a mold, solidification will take place. In the casting process, solidification plays a critical role because the speed at which solidification occurs largely determines the mechanical properties of the casting. The faster the solidification rate, the finer the solidified structure and the higher the mechanical properties. Solidification normally begins on the surface of the casting and moves inward toward the center of the casting or toward the source of feed metal. So solidification can take place in two directions in the casting. One is called progressive solidification occurring from the sidewalls of the casting toward the center. The other called directional solidification occurs toward the source of feed metal. If progressive solidification moves faster than directional solidification, shrinkage voids will occur in the casting. [7]

Like nearly all materials, metals are less dense as a liquid than a solid. So castings shrink will always occur when they cool. There can be three different kinds of shrinkage taking place in the casting: liquid shrinkage, solidification shrinkage and solid shrinkage. Liquid shrinkage takes place when the molten metal cools. Solidification shrinkage occurs from the time the first solid metal appears until the casting is completely solid. Risers can be used to compensate these two types of shrinkage. Solid shrinkage is often called "patternmaker's shrink" because a patternmaker can make a slightly larger pattern than the finished casting dimensions to compensate for the solid shrinkage. The casting cools to ambient temperature after it is completely solidified.

B. Casting Defects

A casting defect [8] is an irregularity in the metal casting process that is very undesired. There are many types of defects which result from many different causes i.e.

1. Design of casting and patterns
2. Molding sand and design of mould and core
3. Metal composition
4. During solidification
5. Melting and pouring
6. Gating and risering [8]

Following defects can occur in sand casting

a. Shrinkage/Warpage defects

Warping is an undesirable deformation in a casting which occurs during or after solidification. Large and flat sections are particularly prone to warpage. Warpage defects may occur due to

- i Insufficient gating system that may not allow rapid pouring of metal
- ii Due to low green strength of the sand mold
- iii Inadequate / inappropriate draft allowance in the pattern / mold cavity.

Warpage is a distortion where the surfaces of the molded part do not follow the intended shape of the design. Part warpage results from molded- in residual stresses, which, in turn, is caused by differential shrinkage of material in the molded part. If the shrinkage throughout the part is uniform, the molding will not deform or warp, it simply becomes smaller. However, achieving low and uniform shrinkage is a complicated task due to the presence and interaction of many factors such as molecular and fiber orientations, mold cooling, part and mold designs, and process conditions. Inadequate thickness, extending over large areas of the cope or drag surfaces at the time the mold is rammed causes rigidity of the pattern or pattern plate which is not sufficient to withstand the ramming pressure applied to the sand. The result is an elastic deformation of the pattern and a corresponding, permanent deformation of the mold cavity. In diagnosing the condition, compare the surfaces of the pattern with those of the mold itself can also be probable cause of warpage.

Warpage in molded parts results from differential shrinkage. Variation in shrinkage can be caused by molecular and fiber orientation, temperature variations within the molded part causes difference in both expansion and cooling and can result in bad warped product. Therefore always maintain the right molding heat temperature, and by variable packing, such as over-packing at gates and under-packing at remote locations, or different pressure levels as material solidifies across the part thickness, proper residence time has to be given for the individual molecules to absorb heat uniformly throughout the material. Otherwise it lead to difference in heat absorbed cool differently. The variables affecting warpage are machine variations like unstable controller, wall thickness, mold temperature, gate location, flow restrictions and bypasses, inherent rigidity of the molded part. If the injection pressure is not enough, the individual molecules do not pack properly which can result in a difference in the way they cool and solidify. Since enough pressure hasn't been provided there is too much space while the material is cooling down and the molecules move while cooling resulting in warpage.[8]

b. Warpage can be minimized in following ways-

- iv Assure adequate rigidity of patterns and pattern plates, especially when squeeze pressures are being increased.
- v Control of pouring temperature.

- vi Resisting or assisting normal contraction at local points by the use of gagers.
- vii Increase injection pressure or time which allows the cooling of the entire part while it is getting constrained.
- viii Study of the shrinkage curve for reinforced materials.
- ix Incorporation of flow aids or flow restrictors help in the alteration of the melt flow profile that in turn prevents warping.
- x In asymmetrical parts provide blind cores during mold planning and design.
- xi Use computer simulation technology.
- xii Multipoint gating system design helps eliminate warpage problems by achieving a high pressure gradient.

C. Methods

Many numerical techniques, including finite element method (FEM) and finite difference method (FDM) etc. have been developed to solve these differential equations with complex boundary conditions arising from material processing.

- a. *Finite element simulation*[12] of casting solidification process is one of the best ways to analyze the process of solidification. It involves the physical approximation of the domain, wherein the given domain is divided into sub-domains called as elements. The field variable inside the elements is approximated using its value at nodes. Elemental matrices are obtain using Galerkin's weighted residual or variational principles and are assembled in the same way, as the elements constitute the domain. This process results in the set of simultaneous equations. The solution of these set of equations gives the field variables at the nodes of the elements.

Following approaches are given as result of which can be classified:

- (1) Modulus and equisolidification time method, which determines the areas that solidify last.
- (2) Criterion function method, which calculates parameters to characterize resistance to interdendritic feeding.
- (3) Direct simulation method, which directly simulates the by mathematically modeling the solidification process.

b. Modulus method

The modulus method is based on Chvorinov's rule that solidification time, T_f of a casting area is proportional to the square of its volume to area ratio, V/A , named modulus.

$$T_f = B (V/A)^2$$

B in this eq. is a factor that depends on the thermal properties of the metal and mold material. [12]

c. Criterion function method

Criteria functions are simple rules that relate the local conditions (e.g., cooling rate, solidification velocity, thermal gradient, etc.) to the propensity to form shrinkage. Since that time, many different criteria functions have been proposed; some were based upon statistical analysis of experimental observations, while others were based upon the physics of one of the driving forces. [12]

d. Solidification simulation using FEM

A FEM based commercial software; ANSYS® is used for solidification simulation. The output of the analysis is thermal gradient and temperature at each node. The analysis is carried out in three steps as given below:

Pre-processing is used to define geometry, material property, and element type for the analysis. Processing phase defines analysis type like transient or steady state, apply loads and solve the problem. It can also be referred as solution phase. Post processing is to review the result in the form of graphs or tables. The general postprocessor is used to review results at one sub step (time step) over the entire model. [12]

The following assumptions are made for the analysis:

- i. Contact resistance between the mold and cooling material is negligible.
- ii. In practice the temperature difference between the mould surface and surrounding air is not substantial hence radiation transfer can be ignored.
- iii. Mould cavity is instantaneously filled with molten metal.
- iv. Outer surface of the mould is initially assumed to be at ambient temperature.
- v. The bottom surfaces of the casting are always in contact with the mould.
- vi. The vertical surfaces of casting are in contact with the mould i.e. no air gap in between.

D. Software

a. Autocast

DR.B.Ravi [3] also used intelligent assistant for casting Engineers (AutoCAST) and describes how it assists in designing, modeling, simulating, analyzing and improving cast products. Autocast software can automate casting design, modeling, simulation, analysis and suggestions for improvising while allowing user to control all decision, also used computer simulation for casting solidification [3,4]. Casting simulation has become a powerful tool to visualize

mould filling, solidification and cooling, and to predict the location of internal defects such as shrinkage porosity, sand inclusions, and cold shuts. It can be used for troubleshooting existing castings, and for developing new castings without shop-floor trials. This will describes the benefits of casting simulation (both tangible and intangible), bottlenecks (technical and resource related), and some best practices to overcome the bottlenecks.

b. Procast

PROCAST [11] uses the finite element analysis (FEA) to simulate casting processes with high accuracy and ease the understanding of solidification processes. Based on powerful finite element solvers and advanced specific options developed with leading research institute and industries, procast provides an efficient and accurate solution to meet the casting industry needs. Compared to a traditional trial-and-error approach, procast is the key solution to reduce manufacturing costs, shorten lead times for mold developments and improve the casting process quality.[11]

c. Solidcast

Solidcast casting simulation software provides visual outputs showing possible problem areas and defects that might occur during the casting process, by using Solidcast during casting process, can reduce the trial casting stage and shorten the lead time. It is one of the best casting simulation software which uses riser design and gating design simulation. Solidcast simulates casting poured in grey iron, ductile iron and virtually any other metal. Solidcast software system is based on the finite difference method (FDM) has been recognised as the most efficient method used for casting simulation and solidification modelling.[11]

Various other casting software's can also be used for simulation purpose. Jean Kor, Xiang Chen, and Henry Hu et al [5] used vector optimization approach that tries to find as many different optimal solutions. Yields good results and provides more flexibility indecision making after applied to the gating and riser design of a sand casting. S. M. Yoo, J. K. Choi [6] Z-Cast™ was used to simulate the fluid flow in a sand mold. The optimal processing parameters for the cooling were obtained from the analysis of fluid flow and solidification. Numerical simulations of mold filling and solidification were used to optimize the casting process. Chokkalingam, Sidharthan [2] used Pro-E software to build a casting model.

Applications and Benefits of using simulation

- Save production resources.
- Develop a new casting faster.
- Optimize existing castings.
- Communicate with designers.

- Accuracy

III. CONCLUSION

By referring various methods, the defect of casting i.e warpage can be reduced. These will helpful to quality control department of casting industries for analysis of casting defects. Also the casting simulation technology has now days become a beneficial powerful tool for casting defect troubleshoot. This will reduce the lead time for the sample casting; improved productivity. In general, warpage can be eliminated by iteratively designing (gating) system and by referring methods which helps in analysis of casting defects may minimises the rejection of casting

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