Multiphysics CAE Simulations of Casting Process for the First Time Right Product Development

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Abstract:

Casting is a manufacturing processes used to produce complex components with lower costs. Casting of ferrous, non ferrous, Aluminum Alloy, graded cast iron, ductile iron and Steel materials are used for automobiles, railways, aerospace and industrial applications. In a casting process, liquid material is usually poured into a mould of the desired shape, and then allowed to solidify. Casting product performance depends on material, flow, Process Temperature, Solidification, Shrinkage and residual stress. In a casting process, not all available resources are utilized effectively which results in low quality of casting, defects and metal wastage. Physics based modeling is increasingly used to optimize product performance, improve quality and reduce defects of casting products. In this paper, phase change solidification process of alloy wheel is investigated for process performance and optimization. Coupled flow, heat transfer and phase change solidification process modeling of casting process of Aluminum alloy wheel is detailed. Multiphysics CAE of casting process will enable first time right casting product development.

Keywords: Casting, product development, physics based modeling, Coupled flow, Heat Transfer, phase change Solidification

1. Introduction

Casting is a 6000 years old and widespread manufacturing processes used to produce complex components with lower costs. Casting/Foundry industry experiences, low quality and productivity issues, due to involvement of number of casting process parameters and coupled physical effects. Even in completely controlled process, defect in casting are observed and hence casting process is also known as process of uncertainty. CAE simulations are increasingly used to provide physics based solution and methods for process control and for eliminating casting defects [1-5]. Figure 1 shows the consumption distribution of casting products. Automobile is one of the major end user of casting products. Cast Aluminum wheels are becoming standard configuration for passenger Cars. The wheel manufacturers are under pressure to develop quality products faster, due to global competition and faster turnaround of models. Multiphysics CAE of casting process can enable virtual product development for the first time right wheel development in compliance with automobile manufacturer's requirement. In this paper, coupled laminar flow, phase change heat transfer and structural analysis is explored for aluminum alloy wheel casting process simulation.

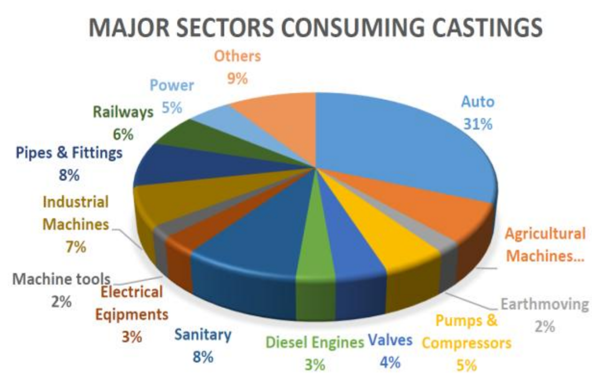

Figure 1. Casting products vs industry distribution

1.1 Casting Overview

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 and further post processed with heat treatment and finishing. The solidified part is also known as a casting, which is ejected or broken out of the mold to complete the process. Casting of ferrous, non ferrous, Aluminum Alloy, graded cast iron, ductile iron and Steel materials are used for automobiles, railways, aerospace and industrial applications. Casting is preferred because highly complex components with less cost and also components can be manufactured with accurate tolerance limits with relatively low capital investment.

Casting product performance depends on material, flow, process temperature, solidification, shrinkage and residual stress. Physics based modeling is increasingly used to optimize product performance, improve quality and reduce defects of casting products. Auto manufacturing sectors is heavily dependent on casting from inception of the industry. In casting there are two types of process are available, they are Expendable Mold Casting and Non-expendable Mold Casting. Expendable Mold Casting Types includes Waste Molding, Sand Casting, Plaster Mould Casting, Shell Casting, and Investment Casting. Non-Expendable Mold Casting includes Die Casting, Permanent Mould Casting, Centrifugal Casting and Semi Solid Metal Casting.

The basic steps involved in Traditional process are, Obtaining the casting geometry, Pattern Making, Core Making, Molding, Melting and Pouring, Cleaning and Other miscellanies finishing Processes. The Parameters for Cost-Effective Metal Casting Design includes Fluidity, Solidification Shrinkage, slag/Dross Formation Tendency, Pouring Temperature, Section Modulus and Modulus of Elasticity.

Application or Use of CAE Simulations can help improve casting process for the first time right product development. Casting process simulation uses numerical methods to calculate cast component quality considering mold filling, prediction of casting mechanical properties, temperature. Lower temperature alloys also can pose thermal stresses and distortion. Simulation accurately describes a cast component's quality up-front before production starts. The casting rigging can be designed with respect to the required component properties. This has benefits beyond a reduction in pre-production sampling, as the precise layout of the complete casting system also leads to energy, material, and tooling savings. Multiphysics CAE Optimization of casting process are generally for die design, avoiding casting defects and better mechanical properties by observing flow speeds, behavior of melt during filling, formation of microstructure, estimation of mechanical properties and residual stress.

2 COMSOL Multiphysics Simulations

In this paper, phase change solidification process of alloy wheel is investigated for process performance and optimization. Production of a cast wheel starts with billet melting and addition of alloys. The molten alloy is filled into a low pressure die from the bottom. The die is heated up to 400 ^{o}C. Suitable cooling circuits are also provided. The wheel casting process involves, die filling, pressure holding, cooling and removal. The filling is relatively short compared to the holding time for phase change solidification. The raw casting is then subjected final finishing process and inspection. The critical filling and solidification part of the process is investigated.

Computational Laminar Fluid flow is considered by describing the fluid velocity, **u**, and the pressure, *p*, according to the following equations,

$$\rho\frac{\partial \mathbf{u}}{\partial t} + \rho\mathbf{u}\cdot\nabla\mathbf{u} = \nabla\cdot\left[-p\mathbf{I} + \mu(\nabla\mathbf{u} + (\nabla\mathbf{u})^T) - \left(\frac{2\mu}{3} - \kappa\right)(\nabla\cdot\mathbf{u})\mathbf{I}\right] + \mathbf{F}$$

$$\frac{\partial\rho}{\partial t} + \nabla\cdot(\rho\mathbf{u}) = 0$$

Eqs 1

Where, ρ is the density, μ is the viscosity, and κ is the dilatational viscosity.

The source term, F in the laminar fluid flow equation relates the velocity at the phase-change interface

$$\mathbf{F} = \frac{(1-\alpha)^2}{\alpha^3+\varepsilon} A_{\mathrm{mush}}(\mathbf{u}-\mathbf{u}_{\mathrm{cast}})$$

eqs 2

Where, α can be seen as the volume fraction of the liquid phase; A_{mush} and ε represent arbitrary constants; and $\mathbf{u}_{cast}$ is the velocity of the melt front.

The heat transport is described by the equation,

$$\nabla \cdot (-k\nabla T) = Q - (\rho C_p \mathbf{u} \cdot \nabla T)$$

Eqs 3

where *k*, *Cp*, and *Q* denote thermal conductivity, specific heat, and heating power per unit volume, respectively.

During the phase transition process, a significant amount of latent heat is released. The total amount of heat released per unit mass of aluminum alloy during the transition is given by the change in enthalpy, Δ*H*. The specific heat capacity, *Cp*, also changes considerably during the transition. The difference in specific heat before and after transition can be approximated by

$$\Delta C_p = \frac{\Delta H}{T}$$

eqs 4

The Phase change heat transfer, laminar flow and Structural analysis COMSOL module [6] is leveraged.

The CAD model of a typical Alloy wheel is used for Finite element Analysis. Figure 2 Shows the FEA mesh of the alloy wheel. Appropriate aluminum alloy materials properties for the wheel, steel die properties and boundary conditions are used. During casting process, liquid melt is injected the mould. The flow process is fast, however, the phase change solidification process is time consuming and complex. Hence, a simplified, axisymmetric model is considered for this investigation of liquid metal solidification due to process parameters. Heat transfer module of COMSOL with Phase change physics is used. In the casting process of alloy wheel, a significant amount of latent heat is released during the phase transition process. The location of the transition front between the molten and solid state is a strong function of the casting flow and the cooling rate in the mould. A transient simulation was performed to study solidification process over time. The flow velocity, pressure, temperature and Volume fraction of phase change are monitored for performance evaluation.

Figure 2 CAD geometry with FEA mesh of typical Automobile Aluminum Alloy Wheel

3. Results and Discussion

Figure 3 and 4 shows, typical contour plots of liquid solid transition phase and at 15 and 60 seconds, respectively. Figure 5 and 6 shows, typical contour plots of liquid solid transition phase and temperature profile at 15 and 60 seconds, respectively. The flow front was animated over process time. The results were post processed to inspect and to avoid turbulent flow, control the flow velocity to minimize flow breaks. A Numerical Design of experiment was performed to correlate the process parameters such as, melt/pouring temperature, process time, pressure build-up, cooling duration to Process optimization to minimize filling path, wastage, porosity. The flow front helps to identify flow pattern. These results will be correlated to casting quality parameters. These investigations will be further used to predict the properties profile of the casted parts by coupling with structural analysis.

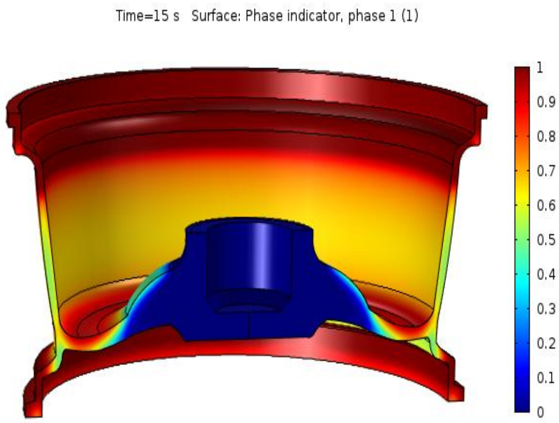

Figure 3. Contour plots of liquid solid transition phase Volume fraction at 15 seconds.

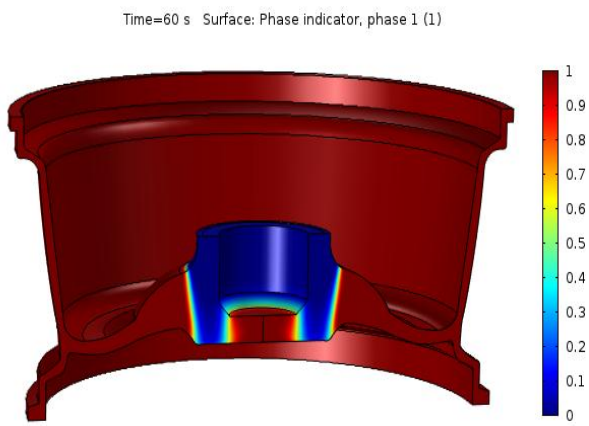

Figure 4. Contour plots of liquid solid transition phase Volume fraction at 60 seconds.

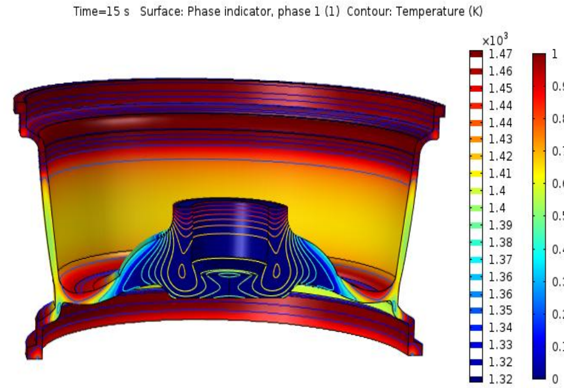

Figure 5. Contour plots of liquid solid transition phase Volume fraction and temperature profile at 15 seconds

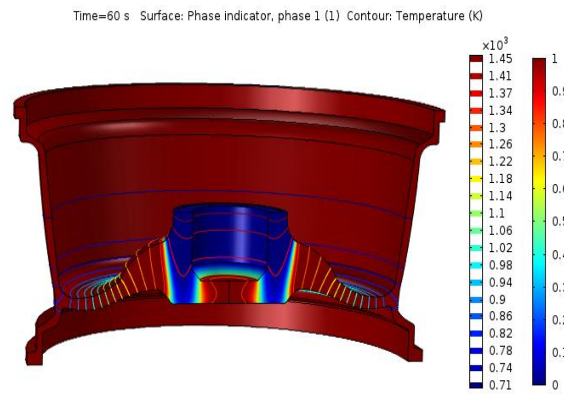

Figure 6. Contour plots of liquid solid transition phase Volume fraction and temperature profile at 60 seconds

4. Conclusions

A brief overview of casting process was given. The problem formulation and simulation details related to coupled phase change heat transfer, laminar flow and structural analysis was given. An aluminum alloy wheel from automobile industry was considered for representative casting process simulation. The COMSOL modeling details were provided. The simulation results related to solidification process and phase change flow front were reported. The correlation potential of process parameters such as, melt temperature, process time, pressure build-up, cooling duration to Process optimization to minimize filling path, wastage, porosity was highlighted. Further, coupled structural analysis will be used for mechanical property prediction. The model will be developed as an online application with COMSOL server backend for cost, process, and performance optimization of casted products.

5. References

[1] Chougule, R.G., and Ravi, B., 2003, casting process planning using case based reasoning. Transactions of American Foundry Society, 111, 2003.

[2] Vijayan T G, "Numerical Simulations of casting Solidification in permanent metallic molds", 26 September 2005, Journals of material processing technology 178(2006) 29-33, 2006.

[3] Rajkolhe R, Khan J G,"Defects, Causes and Their Remedies in Casting Process: A Review ", International Journal of Research in Advent Technology, Vol.2, No.3, March 2014 E-ISSN: 2321-9637

[4] Ravi B, "Metal casting: Computer-aided Design and analysis", PHI, New Delhi, ISBN: 81-203-2726-8, 2005-2008, Fourth print, 2008.

[5] Flori M, Milostean D, Heat Transfer Simulation in Mold During Die Casting of Steel, ACTA Technica Corviniensis – Bulletin of Engineering, ISSN: 2067-3809, Vol VI, No 4, Oct-Dec, 2013.

[6] COMSOL Multiphysics, Introduction to COMSOL Multiphysics and Heat transfer and Fluid flow and Structural analysis manual, version 5.1, 2015.

6. Acknowledgements

The authors would like to thank the ATOA’s Multiphysics CAE R&I initiative (cae.atoa.com) and atoast jyothi foundation (ajf.atoa.com) for the research fund and approval for publication.