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Virtual Casting: State of the Art in Metal Casting Simulation Tools

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Abstract: The demands on the productivity and robustness of metal casting processes for high quality components are continuously increasing. Moreover, the financial considerations necessitate meticulous and reliable planning of the entire casting process before it is actually put into practice. A holistic approach to perform cradle to grave analysis of cast products is simulation-based metal casting. This method allows engineers to model, verify, and validate the process followed by its optimization and performance prediction in virtual reality. This paper provides insights on state of the art in simulation-based metal casting with reference to some case studies. Casting simulations software, mathematical models and solution methods, and casting process simulation together with the results obtained are clearly explained. The current practices revealed extensive utilization of simulation packages for defect minimization, yield maximization, and improved quality. The ongoing research on integration of casting simulations with mechanical performance simulations makes it possible to analyze the serviceability of cast parts. The reliability of cast part in service with dynamic loading of varying thermal and mechanical load cycles can be predicted through this integration. However, more rigorous work is needed in this area, particularly by developing the reliability prediction modules embedded in advanced simulation tools.

Keywords: Metal casting; Simulation; Software; Design; Defects.

عمل القوالب الخاصة بالأدوات القولبة ألافتراضية : أحدث الطرق في سبك المعادن

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الملخص: إن الطلب على إنتاجية ومتانة السبائك المعدنية لإنتاج مكونات عالية الجودة يتزايد على نحو. كما أن الاعتبارات المالية تستلزم تخطيطا دقيقا وموثوقا لعملية السبك بأكملها قبل وضعها موضع التطبيق الفعلي.ولذا فان النهج الشامل لإرساء أساسا لتحليل متزن للمنتجات المسبوكة يكون مبنيا على عملية القولبة الافتراضية. هذا يسمح للمهندسين القائمين عليها بوضع نموذجها والتحقق من صحة انتاجها و اجازتها وبعد ذلك التنبؤ بالأداء الأمثل والأداء الواقعي .وتقدم هذه الورقة نظرة ثاقبة على أحدث ما توصلت إليه تجارب السبك المعدني القائم على القولبة مع الإشارة إلى بعض دراسات الحالة. و تم القيام بشرح واف لبرامج سبك القوالب و النماذج الحسابية وطرق الحل وعملية سبك القوالب جنبا إلى جنب مع النتائج التي تم الحصول عليها. وأظهرت الممارسات الحالية وجود استخدام مكثف لحزم القولبة لتقليل العيوب وزيادة الانتاجية وتحسين النوعية. و تعمل البحوث الجارية القائمة على دمج سبك القوالب مع الأداء الميكانيكي على التمكن من تحليل مدى صلاحية ألأجزاء المسبوكة للعمل , كما يمكن التنبؤ بمدى صلاحية الجزء المسبوك للعمل من خلال دمج التحميل الديناميكي لدورات الحمل الحرارية والميكانيكية المتغيرة ، غير أنه يلزم القيام بمزيد من العمل الجاد في هذا المجال ، ولا سيما من خلال تطوير وحدات التنبؤ بمدى موثوقية أدوات القولبة المتقدمة.

الكلمات المفتاحية : سبك المعادن ، القرص المرن، التصميم ، العيوب.

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1. Introduction

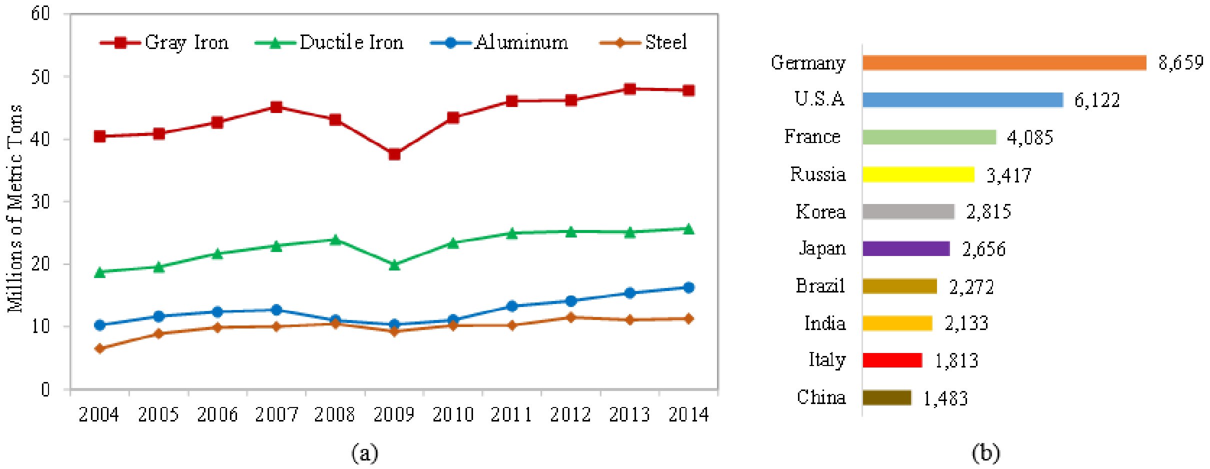
Metal casting is one of the simplest and direct methods of producing near net shape products. The process essentially requires a mold cavity made up of sand, ceramic, or steel, where molten metal is poured and solidified to obtain cast products. A number of casting processes have been developed and modified over time to meet the challenges associated with the new materials to be cast, operating temperatures, complexity of shapes, and high quality etc. The advancements in casting processes are reflected by an upward trend in world cast production during the last decade as shown in Fig. 1(a). In 2014, the estimated amount of metal processed by metal casting is reported to be 105 million metric tons, which is a 2.3 % increase compared to the previous year (AFS 2015; AFS 2016). Moreover, the widespread use of metal casting around the globe is presented in Fig. 1(b), where top ten casting countries are shown with their average production per plant in thousands of metric tons.

It is important that such large production volumes should produce, with higher casting yield, minimum defects, and require mechanical properties. For this reason, metal casting industries have adapted the simulation-based casting methodology, which analyzes the entire casting process and its optimization in a virtual domain before it is actually put into practice. The developments in advanced casting simulation tools have supplanted the conventional trial-and-error approach by a more scientific proof-of-concept approach through computer-aided modeling of the part to be cast, pattern design, methoding, process simulation and virtual optimization (Behera *et al.* 2010). Moreover, defects prediction and minimization via simulation ensure integrity and repeatability in castings together with faster production rate and minimum production cost.

This paper first explains how a casting simulation software works, associated mathematical models and solution methods, and the results obtained by simulation. Next, the current practices in metal casting to minimize defect and improve casting quality are presented. Case studies on gating, runner, and riser design, systematic and autonomous optimization, stress and strain simulations, and integration of casting simulations with mechanical performance simulations are included, discussed and conclusions drawn.

2. Casting Simulations

Casting simulations are extensively utilized in foundries for all cast materials, processes and complex casting shapes. With continuous developments, these simulations are currently used in different stages of product development such as casting design, process determination, flow pattern, design of tooling, quality control and product stress analysis to name a few. Casting design is important as it influences all subsequent stages of product development. Computer-aided casting designs allow for



(a) (b)

Figure 1. (a) Total casting tonnage by alloy (b) Average production per plant (Thousands of Metric Tons)(AFS 2015; AFS 2016).

optimum casting geometries and features, which can be confirmed by filling simulation, solidification analysis, and stress distribution within the cast product. From process determination perspective, the flow characteristic in a mold is revealed and subsequent solidification behavior can be analyzed, which confirms the optimum mold design, appropriate process routing and process parameters. Defect minimization and quality improvements are also possible by simulating the filling and solidification behavior and recognizing the underlying factors affecting product quality and mechanisms of defect formations.

2.1 *Casting Simulation Softwares*

Modelling and simulation of casting processes is complicated due to a host of parameters involved; such as fluid velocity, pressure, geometry of the mold, gating and runner system etc. A range of softwares that have emerged over time are a result of understanding the physical phenomena occuring during a casting process. The relevant mathematical models are either developed or modified and then implemented into computer programs to develop a software (Ravi 2008). Some of the most commonly used casting simulation softwares, which are currently available to researchers and foundrymen, are ProCAST, Flow-3D Cast, MAGMASoft, Nova-Solid/Flow, AutoCAST, SOLIDCast, CastCAE, and CAPCAST etc.

A casting simulation project using commercial softwares generally comprise five stages as shown in Fig. 1 (Ravi 2010). Data gathering refers to all information needed related to CAD model of casting, cast metal properties, mold properties and process parameters etc. Methods design and modeling primarily focuses on how to convert the as cast part model into a three dimensional mold which contains cavities, gating system, runners, risers, cores and feed-aids. Next, the numerical simulation is done after generating the optimum mesh and defining boundary conditions. Visualization of results is done by a post processing module in each simulation software. With the simulation results, it is often possible to identify defects such as hotspots, microporosity, shrinkage, cold shuts and others. Therefore, a step forward in simulation is methods optimization which includes modifications in gating and riser designs, process parameters and material properties, and even in part model to minimize the defects. The final stage, which is termed project closure, includes complete documentation of results, generating methods and analysis reports, capturing images and animations for demonstration at the later stage.

2.2 *Mathematical Modelling and Solution Methods*

Casting simulations begin with modeling the physical phenomena through mathematical equations. In a mathematical perspective, models are expressed as governing equations and boundary conditions. Owing to the non-linearity of models in terms of both geometry and material properties, numerical methods have to be used to avoid non-linearity and thus formulate simultaneous and algebraic equations. The set of developed equations is then used to explain casting process in the form of action-behavior-property relationship (Fu *et al*. 2009). For a metal casting process, the action is supplying molten material to the mold, the behavior is the flow of molten metal within the mold, and the behavior is further decided by properties of the molten metal.

From modeling point of view, three important phenomena in any casting process simulation are mold filling, solidification and cooling, and stress and strain profile of the cast parts. In each of these phenomena, a certain set of governing equations are employed. For example, mold filling is modeled by continuity equation, momentum equation (Navier-Stokes equation) and energy equation (Jolly 2003).

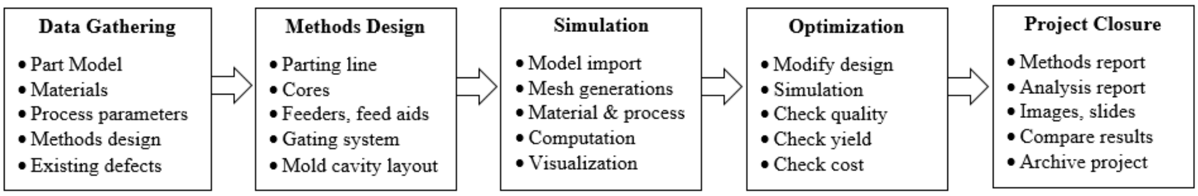


Figure 2. Casting simulation and optimization protocol (Ravi 2010).

Equations (1) to (3) represent the complete forms of continuity, momentum and energy equations respectively and thus modified accordingly if the density is assumed to be constant and/or the molten metal is a Newtonian fluid.

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial_{xj}}\left(\rho U_j\right)=0 \tag{1}$$

$$\frac{\partial}{\partial_t}\left(\rho U_i\right)+\frac{\partial}{\partial_{xj}}\left(\rho U_j U_i\right)=\frac{\partial \rho}{\partial_{xi}}+\frac{\partial}{\partial_{xj}}\left(\lambda\frac{\partial U_i}{\partial X_j}\right)+\rho g_i \tag{2}$$

$$\frac{\partial}{\partial t}\left(\rho C_p T\right)+\frac{\partial}{\partial x_j}\left(\rho C_p U_J T\right)=\frac{\partial}{\partial X_j}\left(\mu\frac{\partial T}{\partial x_j}\right)+Q \tag{3}$$

A variety of methods for solving mathematical equations are available, the most common of which are finite difference method (FDM), finite volume method (FVM), finite element method (FEM), vector element method (VEM), cellular automation method (CA) etc. (Jolly 2002).

Finite Difference Method: It is a numerical method where a complex problem is solved by discretizing the complete region of problem (also known as domain) into a finite number of small portions (also known as control volumes). Material properties are assumed to be constant throughout the volume. Therefore, for high accuracy of the results, the domain should be divided into a maximum number of control volumes possible, taking into account the computational time. FDM is a differential scheme, which is approximation of Taylor series expansion. Calculations are iterative and done at a predetermined time-step. The results can be stored at the end of each time-step or after a pre-determined numbers of steps (Jolly 2003).

Finite Volume Method: Unlike FDM, FVM is an integral scheme. Although the idea of discretizing the domain into small control volumes remains the same, the use of integral formulations is advantageous in treating the Neumann boundary conditions as well as that of discontinuous source terms due to their reduced requirements on the regularity or smoothness of solution.

Finite Element Method: FEM discretizes the complete domain of the problem into small pieces; however, they are now termed as elements. Each element is made up of nodes (corner points) and edges, which store material properties to be used in computation. The solution is done by using these values to determine a quantity for these specific points (also known as Gauss points) within the elements. The position of these points in elements is a function of the integration applied, initial coordinates of the nodes, and the element shape (Jolly 2003). Values of variables, which are considered to be constant in FDM/FVM across the elements, are calculated using some interpolation function. However, the treatment of time in an iterative and step-wise manner is similar to FDM/FVM.

Vector Element Method: This approach to casting simulations is based on determining the largest thermal gradient at any point inside the casting, which is given by the vector sum of flux vectors in all directions from that point (Amin *et al.* 2014). Vector element method is relatively simple when compared to other numerical techniques but provides reliable and robust results (Ravi 2005; Sutaria *et al.* 2014).

In some instances a combination of two or more techniques may also be employed, the examples of which are cellular automation finite element (CAFE) method proposed by (Rappaz *et al.* 1998), and a hybrid method for casting process simulation by combining FDM and FEM (Si *et al.* 2003). The final simulation results, however, are representative of casting process and properties, qualities and defects of cast products irrespective of the type of solutions discussed above.

2.3 Simulation Results

Casting simulations result in three major aspects of a casting process: Filling, Solidification and Stress Analysis. Mathematical modeling and simulation of conservation of mass, momentum and energy in a filling process provides information about velocity of molten material within the mold cavity, the direction of flow, temperature and pressure at various instances within the mold. Physical and thermal characteristics of the filling process are derived from these results, some of which are flow front progression, turbulence in flow, filling evenness, air and gas entrapment, temperature profile, filling sequence, velocity profile of molten metal, odd behaviors such as splashing, misruns, cold shuts etc. during filling.

Solidification in the casting process is generally complex, where physical, thermal and metallurgical phenomena take place simultaneously. Solidification simulation provides information about how these phenomena are occurring in process conditions together with the defects that might arise during solidification phase. Some key findings of a solidification simulation include cast area that solidifies last, solidification sequence, validation of cooling design, validation of runner design, defects due to shrinkage and microporosity, appropriate riser geometry, size and location within the mold.

The stress and strain simulation demonstrates the state of cast parts after ejecting from the mold. The results of these simulations may include identification of dimensional inaccuracies, residual stress generation and distribution in cast part; defects arise due to stress and strain, temperature profile in ejected cast part, design improvements in casting design such as modifications in riser design to reduce stresses etc.

3. Current Practices in Simulation-Based Metal Casting

The current practices in simulation-based metal casting brought solutions to many problems in foundries. High quality defect free castings are now produced by developing an in-depth understanding of the areas such as: (a) filling and solidification during several casting processes, (b) design of runner and gating systems, (c) design of feeding systems (locations and number of risers), (d) casting process parameters (thermo-physical data, injection parameters etc.), (e) stress distribution in cast products, and (f) quality control and assurance of the cast products. Some of the efforts in these areas are as follows.

3.1 Gating, Runner, and Riser Design Optimization

Mi *et al*. (2009) used casting simulations to modify gating and riser system of a valve block. The original design with two in gates and rounded-rectangular riser geometry as shown in Fig. 3(a) resulted in defects *i.e*. shrinkage and cold shut. The new casting design, as shown in Fig. 3(b), comprised a single in gate together with cylindrical risers as they allow more liquid metal during solidification. Chills were added to help solidification in the bottom region of casting and shrinkage was overcome via modified riser design. The final casting was reported to be free from surface cracks on the valve body.

Sun *et al*. (2008) presented multiple objective optimization for gating system of a cylindrical magnesium alloy casting. The optimum gating system was selected by changing four parameters: ingate height, ingate width, runner height, and runner width as shown in Fig. 4(a). The main criteria for casting quality were filling velocity, shrinkage porosity and yield. Bottom filling approach was employed as shown in Fig. 4(b). It was concluded that runner with small height and large width is effective in reducing metal velocity at the ingate which is consistent as reported by Mi *et al.* (2009); and Hu *et al.* (2000).

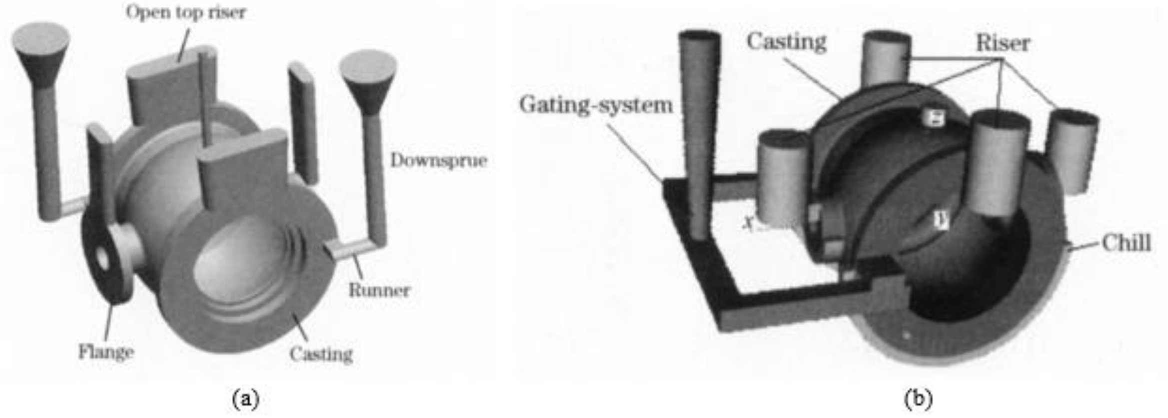


Figure 3. Casting design for a valve body (a) original and (b) modified. (Mi et al. 2009).

Kermanpur *et al*. (2008) simulated the filling and solidification sequence of brake disc and flywheel in multi-cavity molds. It was reported that a symmetrical mold configuration for flywheel, as shown in Fig. 5(a), provides uniform filling contrary to the one for brake disc presented in Fig. 5(b). Simulated hotspot reflected as micro-shrinkage in brake disc for which lower superheat temperature was recommended. In another work by Choudhari *et al*. (2014), the hotspot defect was eliminated by simulating an exothermic sleeve around the riser which, delayed solidification time as shown in Fig. 6. Riser system design was simulated based on quality, feeding yield and feeding efficiency followed by experimental validation which also resulted in cast products free from shrinkage defect.

Liu *et al*. (2007) simulated the decomposition of expanded polystyrene (EPS) pattern in lost foam casting process using Flow 3D. The conventional constant heat transfer coefficient (CHTC) approach is modified by incorporating the variability in the heat transfer coefficient (VHTC), which resulted in a better agreement

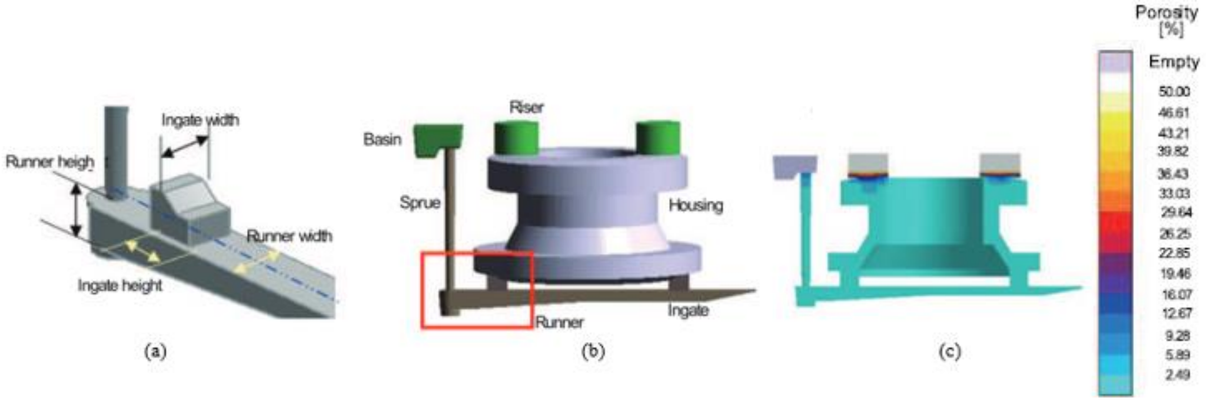


Figure 4. (a) Gating parameters (b) Gating system design and (c) Shrinkage porosity prediction in cylindrical magnesium casting (Sun et al. 2008).

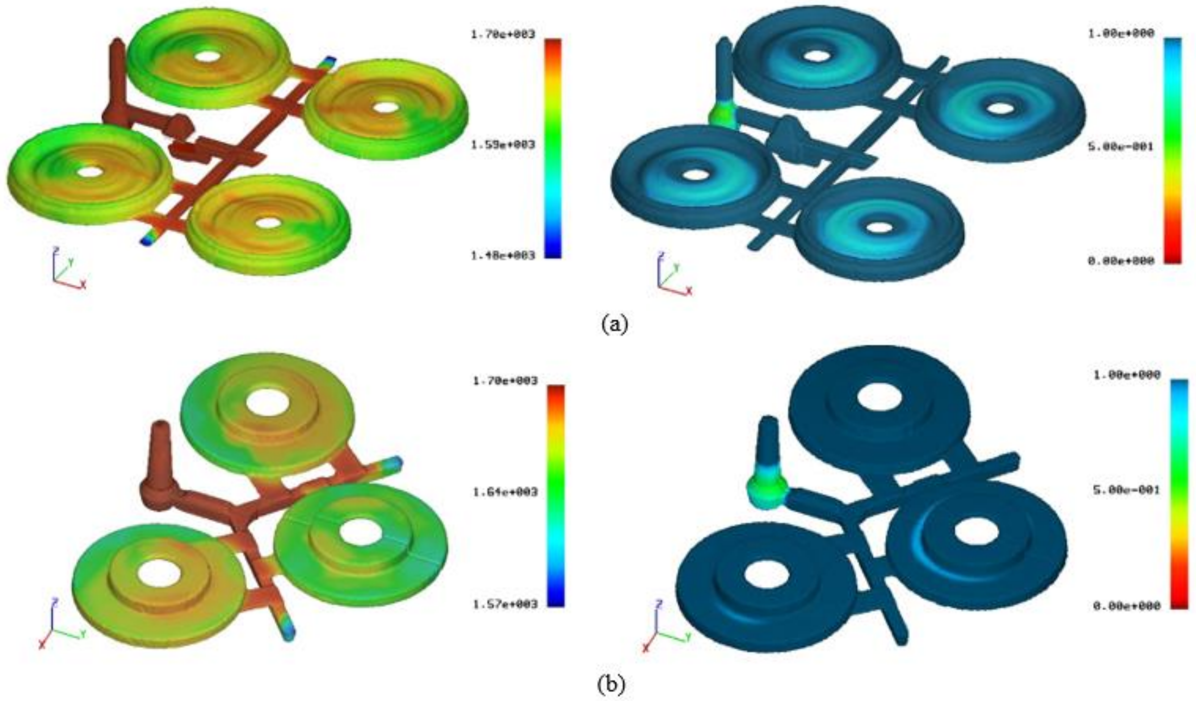


Figure 5. Final results of filling (left) and solidification (right) for (a) Flywheel and (b) Brake disc.

of simulation and experimental results. The effect of temperature on mold filling time was also studied and it was reported that mold filling time predicted by VHTC model were found close to the experimental results. Defects in castings are predicted via both CHTC and VHTC models where the main mechanism of defect formation was the meeting of metal fronts entering from different in gates. The results of defect predictions with three in gates as well as a modified two in gates system are presented in Fig. 7, which confirms reductions in casting defects with fewer in gates.

Nimbulkar *et al.* (2016) optimized the gating and feeding system design for casting a wear plate using AUTOCAST. The original design for casting utilized a vertical gating system, which resulted in casting defects. In this study, the vertical gating system was replaced by a horizontal gating system design. The existing and new casting designs were simulated by AUTOCAST followed by their experimental validation. The final cast products were examined through ultrasonic inspection. It was found that vertical gating system was not suitable for thick casting components due to multiple casting defects observed during solidification. However, the horizontal gating system with symmetrical gates and risers enabled uniform flow of the melt together with minimized porosity in the final casting. In total, the gating and feeding system related defects are found to be reduced by 30%.

3.2 Systematic Autonomous Optimization

A recent approach to improve simulation-based casting is systematic and autonomous optimization, where softwares are used as test field or virtual experimentation. Sikorski *et al.* (2012) optimized the gating system of a simple casting layout using MAGMA Soft, which follows the sequence as shown in Fig. 8(a). Owing to a multi-cavity mold, it was aimed to reduce the filling time between the cavities to minimize defects due to air entrapment. The results of initial situation and final optimized solution using the filling time difference criterion are presented in Figs. 8(b), and 8(c) respectively. The final casting after autonomous optimization is found to be free from casting defects especially due to air entrapment and oxides.

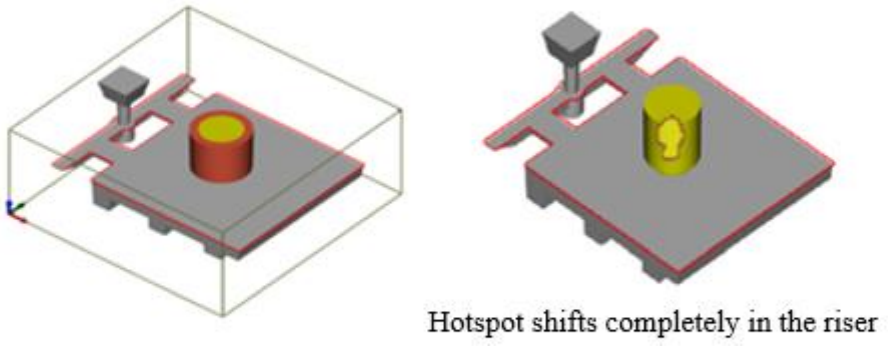


Figure 6. Effect of exothermic sleeve on the position of hotspot in stepped plate casting (Choudhari et al. 2014).

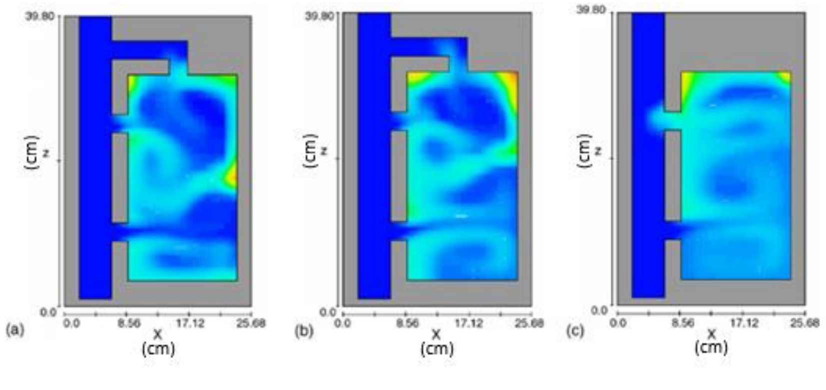


Figure 7. Formation of casting defects by (a) CHTC model; (b) VHTC model; and (c) modified model with two in gates (blue and red represents lowest and highest probability for defects respectively) (Liu et al. 2007).

Hahn *et al*. (2010) compared the design of experiments (DOE) with virtual autonomous optimization for steel casting. The number, location and dimension of the chills and feeders were investigated as shown in Fig. 9(a) to check their effect on the shrinkage distribution. The results, as shown in Fig. 9(b), demonstrate that autonomous optimization led to further reduction in shrinkage by fine tuning the chill size. The autonomous optimization was also done for a ductile iron wind turbine hub to control shrinkage porosity. Moreover, the configuration of runners in a multi-cavity mold for casting six parts was also optimized in the same study (Hahn *et al*. 2010).

Sturm *et al*. (2007) performed the autonomous optimization for casting a head cap in a multi-cavity mold. The actual mold design contained a single cavity where successful filling was achieved through specifically designed gate and a slightly slanted runner as shown in Fig. 10(a). A multi-cavity mold was designed and optimized to achieve similar melt velocities and directions as it was already obtained in single cavity mold. Moreover, minimization of air entrapment was also set as another criterion for optimization. In total, only 1 out of 106 designs for right-hand runner and 2 out of 97 designs for left-hand runner were qualified meeting all objectives of optimization. The flow patterns for single and multi-cavity molds are presented in Fig. 10(a) along with the actual head cap castings in Fig. 10(b).

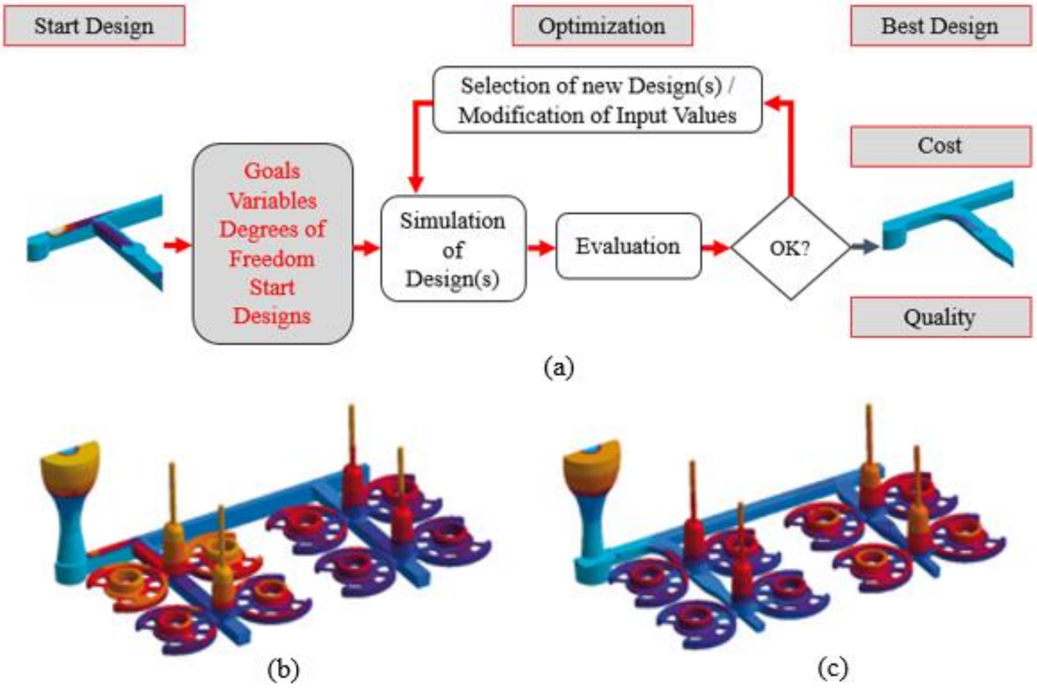


Figure 8. (a) Schematic sequence of optimization in MAGMASOFT (b) Initial situation and (c) Final optimized solution (Sikorski et al. 2012).

Figure 9. (a) Feeder and chills in cope (left) and drag (right) (b) Shrinkage distribution by autonomous optimization (left) and DOE (right) (Hahn et al. 2010).

3.3 Stress and Strain Simulations

The application of numerical simulation to distortion and stress-related problem in casting was presented by Egner-Walter *et al*. (2013). The study first explained the formation of residual stresses and distortion in casting followed by simulation of die cast rear door lock panel for a passenger car. Figure 11(a) represents the temperature field at ejection and it forms the basis for the formation of stresses and deformation during solidification and cooling to room temperature. The runner being hotter contracted more in the subsequent cooling phase and pulled the casting inwards toward it as shown in Fig. 11(b). The swan neck moved in an upward direction, as the upper side of the casting, which faced the shot slug, had a higher temperature than the lower side after ejection. Another problem of hot tears, especially important for high pressure die castings, was also investigated by Egner-Walter *et al*. (2013) by simulating the hot tear criteria for a flywheel as shown in Fig. 12. It was suggested that hot tears can be avoided by modifying process parameters and cooling conditions, or by minor changes in the geometry of casting.

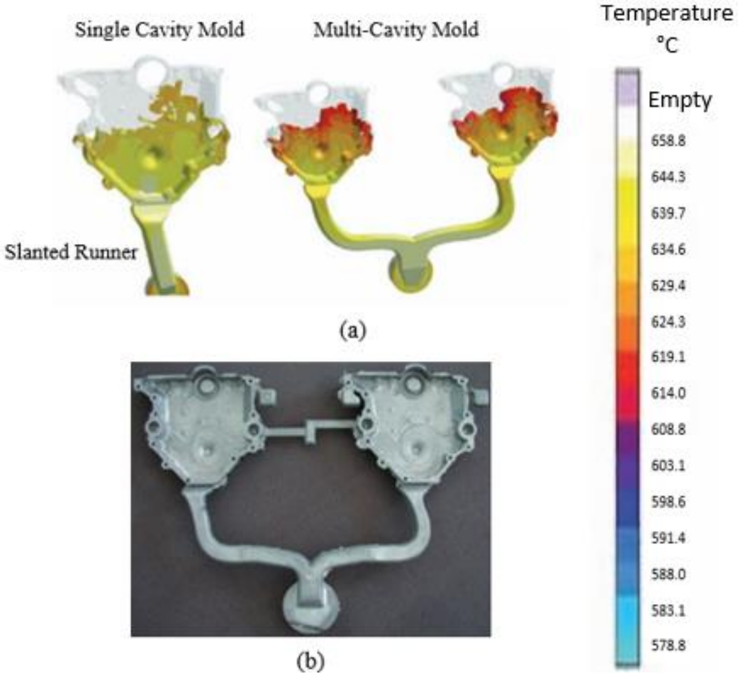


Figure 10. (a) Identical flow patterns in single and multi-cavity molds and (b) actual castings after autonomous optimization (Sturm et al. 2007).

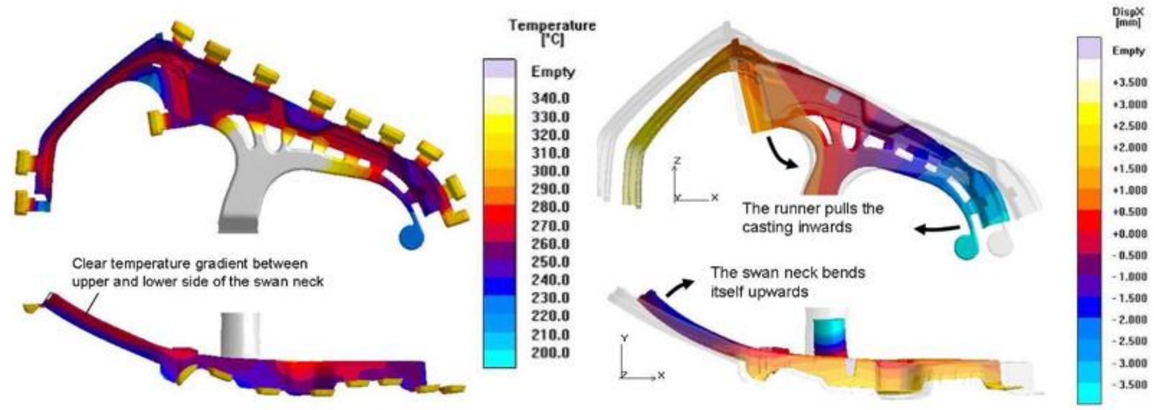


Figure 11 (a) Temperature distribution in casting and runner at ejection and (b) Deformation of the casting after cooling to room temperature: original geometry (semitransparent grey) and deformed geometry (Egner-Walter et al. 2013).

Hartmann (2013) studied the stress generation and distribution due to material combinations in light-weight cast components. Engine blocks are one such application where the grey iron liners are set into the molds and preheated before pouring molten aluminum. The molten metal gets in contact with liner cools rapidly and solidifies quickly which sometimes results in incomplete filling of the mold. Certainly, residual stresses are generated due to a non-uniform temperature distribution in the cast part. Since, aluminum shrinks onto the iron liners, tensile stress is generated in aluminum whereas the liner experiences compressive stress, together with other internal stresses as shown in Fig. 13. It is reported that the tensile residual stress observed in aluminum between the liners is high, however, any crack in this area does not affect the rigidity of cylinder block at operating temperature. For stress minimization, it was suggested to use the high pre-heat temperatures of the liners to decrease the tensile residual stress in the seam between liners.

3.4 Casting Simulations Integrated with Mechanical Performance Simulations

Recently, casting simulations are combined with mechanical performance simulations to investigate the life of cast products in service. The effect of casting quality on service life is analyzed by taking the predictions of defects such as shrinkage and porosity from casting simulation results and maps them with stress and fatigue life simulations.

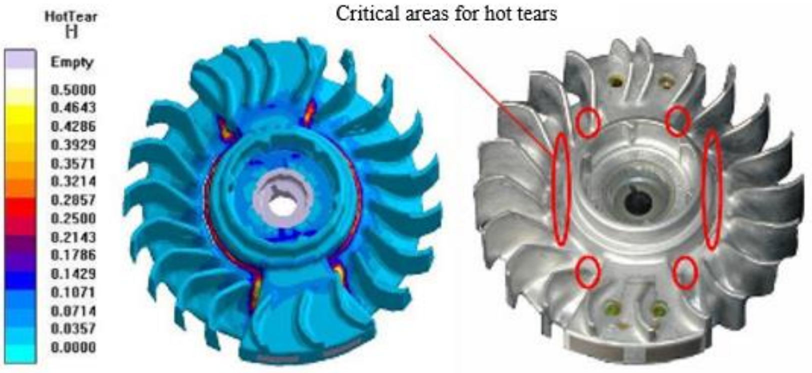


Figure 12. Prediction of hot tears in a flywheel casting using hot tear criterion (Egner-Walter et al. 2013).

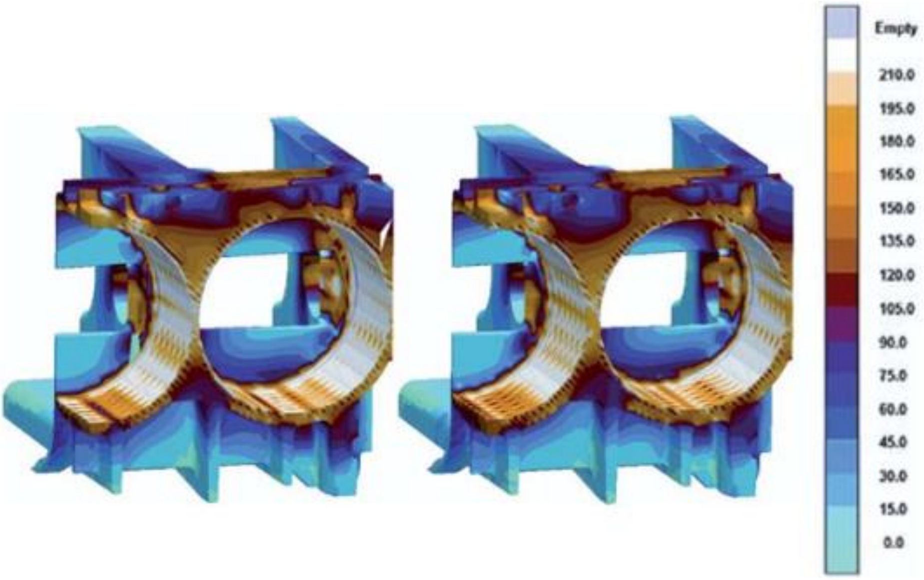


Figure 13. Internal stress in gap between two liners and uneven stress around the liner. High stress (left) in closer distances and low stress (right) in larger distances of the liners. (Hartmann 2013).

Bordas *et al*. (2006) studied the integration of foundry process simulations, non-destructive evaluation, stress analysis, and damage tolerance simulations to casting design as shown in Fig. 14. Casting simulations are done to determine any porosity-related defects by using a radiographic inspection simulation tool (XRSIM). Failure caused by the predicted defects is determined by a fatigue crack growth simulation based on extended finite element method. This integrated approach enabled for an “accept or reject” criteria to be set at an early design stage and allows for damage tolerant design strategies. Dørum *et al*. (2007) studied the effects of porosity and surface quality on structural behavior by mapping results of casting simulation by MAGMASOFT with a two-dimensional (shell element) finite element model developed in LS-DYNA. The study was primarily focused on mechanical performance of thin walled cast magnesium components subjected to quasi-static loading conditions. Olofsson *et al*. (2012) presented software that incorporates the prediction of casting simulation software into a finite element method. The software is validated through a test case of ductile iron component.

In another study by Hardin *et al*. (2012), the fatigue life of a cast steel component in service is predicted by utilizing the porosity predictions of MAGMASOFT in FE simulations. A block-diagram of the methodology used in the analysis is presented in Fig. 15. This approach was first validated for a simple geometry of tensile test specimen by comparing experimentally obtained and the predicted crack initiation fatigue lives. The difference was reported to be within one decade that is thought to be very good for fatigue life prediction.

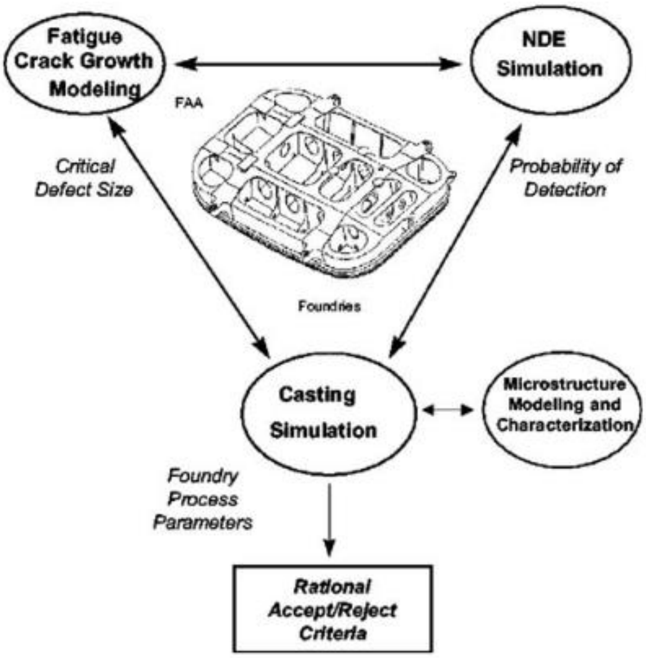


Figure 14. Integration of NDE simulation, casting modeling, and damage tolerance simulation (Bordas et al. 2006).

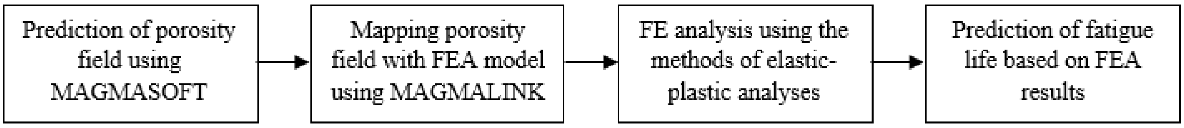


Figure 15. Integration of MAGMASOFT results in ABAQUS for fatigue life prediction.

4. Conclusion

The key conclusions and recommendations from this study are summarized as follows: (i) Casting simulations are capable of examining the effect of several process variables in producing sound castings. (ii) Modeling boundary conditions precisely in a casting simulation software followed by its experimental validation is challenging. (iii) Cast products are often produced with residual stresses the accurate prediction of which can help in suggesting appropriate heat treatments. (iv) Autonomous optimization must be utilized at its best to improve quality. (v) Reliability of cast part in service with dynamic loading of varying thermal and mechanical load cycles can be predicted through integration of casting simulations with mechanical performance simulations. However, more rigorous work is needed in this area particularly by developing the reliability prediction modules embedded in advanced simulation tools. (vi) All casting simulation softwares are not created equal, based upon the in-house capabilities of foundry skills, CAD expertise available, and level of accuracy and integrity needed in cast products, it is imperative to very carefully see and compare all features available in each software and buy the software which meet your goals and provide best benefit over cost ratio.

Conflict of Interest

The authors declare no conflicts of interest.

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References

AFS (2015), 49th Census of World Casting Production Modest growth in worldwide casting market.

AFS (2016), Modern Casting census of world casting production – steady growth in global output.

Amin LD, Patel S, Mishra P, Joshi D (2014), Rapid development of industrial castings using computer simulation. *Indian Foundry Journal* 60(8).

Behera R, Das S, Dutta A, Chatterjee D, Sutradhar G (2010), Comparative evaluation of usability of FEM- and VEM-based casting simulation software. In *58th Indian Foundry Congress*, Ahmedabad, India

Bordas SPA, Conley JG, Moran B, Gray J, Nichols E (2006), A simulation-based design paradigm for complex cast components. *Engineering with Computers* 23(1): 25–37.

Choudhari CM, Narkhede BE, Mahajan SK (2014), Methoding and simulation of LM 6 sand casting for defect minimization with its experimental validation. *Procedia Engineering* 97: 1145–1154.

Dørum C, Hopperstad OS, Lademo OG, Langseth M (2007), Numerical modelling of the structural behaviour of thin-walled cast magnesium components using a through-process approach. *Materials & Design* 28(10): 2619–2631.

Egner-Walter A, Kothen M (2013), Using stress simulation to tackle distortion and cracking in castings. *Metallurgical Science and Tecnology* 24(2).

Fu MW, Yong MS (2009), Simulation-enabled casting product defect prediction in die casting process. *International Journal of Production Research* 47(18): 5203–5216.

Hahn I, Sturm JC (2010), Autonomous optimization of casting processes and designs. In *World Foundry Congress, Hangzhou, China October*, 16–20.

Hardin RA, Beckermann C (2012), Integrated design of castings: effect of porosity on mechanical performance. *IOP Conference Series: Materials Science and Engineering* 33(1): 012069.

Hartmann G (2013), Material combinations in light weight casting components. *Casting Plant and Technology* 4: 32–37.

Hu BH, Tong KK, Niu XP, Pinwill I (2000), Design and optimization of runner and gating systems for the die casting of thin-walled magnesium telecommunication parts through numerical simulation. *Journal of Materials Processing Technology* 105(1–2): 128–133.

Jolly M (2002), Casting simulation: How well do reality and virtual casting match? State of the art review. *International Journal of Cast Metals Research* 14(5): 303–314.

Jolly M (2003), Castings. In *Comprehensive Structural Integrity* 377–466. Elsevier

Kermanpur A, Mahmoudi S, Hajipour A (2008), Numerical simulation of metal flow and solidification in the multi-cavity casting moulds of automotive components. *Journal of Materials Processing Technology* 206(1–3): 62–68.

Liu XJ, Bhavnani SH, Overfelt RA (2007), Simulation of EPS foam decomposition in the lost foam casting process. *Journal of Materials Processing Technology* 182(1–3): 333–342.

Mi G, Liu X, Wang K, Fu H (2009), Application of numerical simulation technique to casting process of valve block. *Journal of Iron and Steel Research, International* 16(4): 12–17.

Nimbulkar SL, Dalu RS (2016), Design optimization of gating and feeding system through simulation technique for sand casting of wear plate. *Perspectives in Science* 8: 39–42.

Olofsson J, Svensson IL, (2012), Incorporating predicted local mechanical behavior of cast components into finite element simulations. *Materials and Design* 34: 494–500.

Rappaz M, Rettenmayr M (1998), Simulation of solidification. *Current Opinion in Solid State and Materials Science* 3(3): 275–282.

Ravi B (2005), Metal casting: computer-aided design and analysis. New Delhi: Prentice-Hall of India.

Ravi B (2008), Casting simulation and optimization: Benefits, Bottlenecks, and Best Practices. *Indian Foundry Journal January* (Special Issue).

Ravi B (2010), Casting simulation – best practices. In *Transactions of 58th IFC*, Ahmedabad, India

SiH M, Cho C, Kwahk SY (2003), A hybrid method for casting process simulation by combining FDM and FEM with an efficient data conversion algorithm. *Journal of Materials Processing Technology* 133(3): 311–321.

Sikorski S, Dieckhues GW, Sturm JC (2012), Systematic optimization of aluminum sand casting gating systems. *American Foundry Society*.

Sturm C, Seefeldt R (2007), Two for one– transferring proven filling characteristics from a single to a two cavity die casting die. *Casting Plant & Technology* 3: 44–52.

Sun Z, Hu H, Chen X, Wang Q, Yang W (2008), Gating system design for a magnesium alloy casting. *Journal of Materials Science and Technology* 24(1): 93–95.

Sutaria M, Ravi B (2014), Computation of casting solidification feed-paths using gradient vector method with various boundary conditions. *The International Journal of Advanced Manufacturing Technology* 75(1–4): 209–223.