National conference on Recent Advances in Mechanical Engineering
16-17, March, MED,UCE,Osmania University, Hyderabad-500007

EVALUATION OF DIE CASTING DIE DESIGN FOR AIRCRAFT NOSE WHEEL HALF HUB CASTING TO MINIMISE POROSITY AND HOT CRACKS USING SOLIDCAST

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ABSTRACT

Aluminum castings intended for aerospace applications are governed by stringent specifications, those that will be fitted on wheel and brake system of military aircraft are governed by MIL-W-5013L, ASTMB108/B108M & ASME155 for shrinkage porosity and other parameters. Creation of shrinkage porosity is influenced by factors such as: temperature history, cooling rate and temperature gradient which affect the solidification phenomenon and heat transfer taking place in the mould. The location and geometry of gate and runner largely influence heat transfer in mould. A methodology has been proposed to evaluate die design using Solidcast simulation software. Aircraft nose wheel half hub casting was chosen. For developing die design, three gating systems having one, two and three gates were considered. For each type of gating systems two different runner cross-sectional dimensions were taken and draft angle of 0.25 degree and 0.5 degree was provided in each case, thus developing twelve die designs for evaluation using Solidcast simulation software. Mould filling time, maximum and minimum temperatures of casting and mould were recorded at regular intervals of time till solidification is completed. The post simulation iso-surface pictures have been plotted for material density function (MDF), Hot Spot (solidification time), Hot Spot (Critical Fraction Solid Time) and Critical Fraction Solid Time. The acceptance criteria was fixed as MDF would be at least 0.999 and hot spots would not be present. Accordingly the models have been evaluated and results were interpreted with the help of graphs plotted for maximum and minimum casting and mould temperatures, percentage of solidification, the difference between the maximum and minimum casting temperature and time derivative of maximum casting temperature with respective to time. Conclusions are drawn and recommendations are placed.

Key Words: Temperature Gradient, Cooling rate, Material Density Function, Hotspots, Critical Fraction Solid Time, Niyama Criterion.

3. INTRODUCTION

The aluminum castings intended for military and aeronautical applications need to comply with stringent quality standards. The castings used on wheel and brake assemblies for military aircraft will have to comply with MIL-W-5013L specification. One of the most important criteria for acceptance of these castings is shrinkage porosity. Temperature gradient, cooling rate together with temperature, decide the locations of porosity. Solidification phenomenon and heat transfer, influence these parameters. The design and location of feeder system have large bearing on heat transfer taking place in the mould. Hence, different locations and geometry of feeder system have influence of shrinkage porosity. For evaluating and finding optimum location and geometry, it is proposed to use simulation package for casting process.

In this paper an attempt has been made to provide a comprehensive methodology to evaluate and select the best design layouts for aluminum casting die's using Solidcast software.

4. LITERATURE REVIEW

Solidification of castings is a non-Linear transient phenomenon involving change of phase with liberation of latent heat from a moving liquid – solid boundary. The heat is transferred from the molten metal from the solidified portion of the casting, then through the air gap to casting- mould interface and finally through the mould. All the three modes of heat transfer viz., conduction, convention, and radiation are involved. The results from the solidification analysis give the location and extent of shrinkage porosity defects. This requires the temperature history of all points inside the casting. The most important instant of time is when hottest region inside the casting is solidifying.

Sirrell, et al., [1], were able to simulate behavior of the molten aluminum close to reality, as they studied the behavior of the molten aluminum filling of different gating system by optical means and correlated the measures to obtain behavior by some simulators. Jain et al [2] made comparative study among SOLIDcast, Magma Soft and Flow 3D and described how Niyama Criterion, which is used to credit shrinkage porosity defects, is evaluated in each case. Li et al [3] carried out numerical simulation of grey iron butterfly valve using hydro dynamics software Flow 3D.

Couturier and Rappaz [4] described modeling of porosity formation in multi component alloy. Hirt [5] showed how by using a simulation package viz., Flow 3D, it is feasible to predict core shooting, drying and defect development in sand casting.

Chandra [6] presented the basic concept for comprehensive finite element base computer simulation method for prediction of hot cracks, residual stress and distortion in precision castings using sequential thermo – mechanical approach, besides reviewing the existing capabilities of several industry standard commercial and research finite element codes. Dominique et al., [7] described the development and use of simulation in the design of blown cores and moulds.

Reikher et al., [8] demonstrated the application of one dimensional numerical simulation to optimize process parameters of a thin wall casting in high pressure die casting. Sirvio and Wos [9] demonstrated the use and advantage of Flow 3D software which can simulate surface defects, air entrainment, filters, core gas problems and cavitations.

Ngadia et al., [10] emphasized that successful computer simulation could help reduce the number of trials and cut down the lead time in design of new products by better understanding the complex mechanisms and inter play of different process parameters.

The present work proposes to take nose wheel half hub to be used on a military aircraft and develop the most optimum die design in terms of the acceptance criteria as stipulated in the relevant standards. Here, twelve die designs were chosen with different gate and runner design combinations.

These die designs have been evaluated through simulation using SolidCast software, the die designs that produce the castings which meet the acceptance criteria have only to be adopted. This work is intended to provide methodology of arriving at an optimum die design for a given casting which meets the prescribed requirements as an alternative to a rather expensive die try out.

5. PREPARATION OF DIE DESIGN LAYOUT

For this work, half hub for aircraft nose wheel was chosen with outer diameter 198.755mm. After adding machining and shrinkage allowances to the detail drawing dimensions the casting model was developed, as shown in Fig.1. The cross-sectional details are shown in Fig. 2. For development of die design, three types of gating systems i.e, with one, two and three gates were considered. The cross-section for sprue and runner were chosen as trapezium and sprue area was kept as 28 sq mm. For each gating systems, two different rectangular cross-sections were chosen for gate and for each rectangular sections two different drafts i.e, 0.25 degree and 0.5 degree were provided. The gating ratio was maintained as 1:4:4. Thus, twelve different die design were developed in Unigraphics Nx5 software.The cross-sectional view of Die is shown in Fig 3. The model wise, Cross-sectional details of sprue, runner, gate and draft angle provided are given in Table 1. These three dimensional models were exported to Solidcast software to carry out casting simulation.

Fig 1. Three- Dimensional Model of Nose Wheel Half Hub Casting

Fig 2. Cross-sectional view of Nose Wheel Half Hub Casting

Fig 3. cross – sectional view of die

No. of gates	Sprue Cross-section area (trapezium) mm^2	Runner cross-section area (trapezium) mm^2	Gate cross-section area (rectangle) mm^2	Draft angle in degree's
1	34.5	138	92x1.5=138	0.25
1	34.5	138	69x2=138	0.25
1	34.5	138	92x1.5=138	0.50
1	34.5	138	69x2=138	0.50
2	34.5	138	46x1.5x2=138	0.25
2	34.5	138	34.5x2x2=138	0.25
2	34.5	138	46x1.5x2=138	0.50
2	34.5	138	34.5x2x2=138	0.50

3	34.5	138	30.666x1.5x3=138	0.25
3	34.5	138	23x2x3=138	0.25
3	34.5	138	30.666x1.5x3=138	0.50
3	34.5	138	23x2x3=138	0.50

Table 1 Cross sectional details of feeder system for Nose Wheel Models.

6. PREPARATION FOR CASTING SIMULATION.

The pouring height, mould filling time and pouring temperature were taken as 102mm, 11 sec and 750^0 C respectively. After importing 3 – dimensional CAD models in solidcast, the following 8 windows were to be completed. Each part should be assigned with a mesh priority number and composition of metal to be poured, should be entered as silicon 0.85%, magnesium 1.2%, strontium 0.3%, molybdenum 0.7% and aluminium 96.5%. then the niyama point and critical fraction solid point, which indicate the directional solidification in casting, should be set as 40% and 35% respectively. Mould material properties were chosen and then, after finishing the water channel were selected as 34 W/sq.m.^{0}K, 1135 W/sq.m.^{0}K, 710 W/sq.m.^{0}K, 40 W/sq.m.^{0}K, 1532 W/sq.m.^{0}K respectively. Thereafter ambient temperature was set at 32.222^0C and the three applied parameters to permanent mould viz., reduce mould/metal heat transfer co-efficient at solidus point, solid cast fill turn horizontal and thermo couple time step as 1 were selected. Finally mesh name was selected as mesh 5 and number of nodes were taken as 1 million.

After inputting all the above parameters, the simulation was run and the results were analyzed.

7. SIMULATION DESIGNS.

The following post simulation data was recorded.

(1) Filling status and solidification time: In all twelve models mould filling was completed in 11 seconds and solidification time varied from 1.5682 to 1.7509 minutes for ten models and for the remaining two models, it was 5.267 and 5.9672 minutes.

(2) Critical fraction solidification time: This is the time in minutes, for each part of the casting to reach Critical Fraction Solid Point at which alloy is solid enough that liquid feed metal can no longer flow. This is an indication for directionality of solidification.

(3) Temperature Gradient: It is a measure of how much change in temperature there is, from point to point, on the casting. This is calculated at each node within the casting as that point hits Niyama point on the cooling curve. High temperature gradient is preferred.

(4) Cooling rate: This is measured at each point in the casting as the point hits Niyama point on the cooling curve.

(5) Material Density Function (MDF): It is a measure of how much of the metal remains at each point in the casting. It is indicated by a number that varies from 0 to 1. A value of zero means that the metal has been completely drained from the part of the casting and value of 1 indicates, completely sound metal. In accordance with the applicable standards MDF is chosen between 0.999 and 1.0 i.e. if any point in the casting is observed to have MDF 0.999, it is rejected.

(6) Hot Spots: Hot spots or thermal centres are plotted within the casting by comparing either solidification time or critical fraction solid time of point within local areas. In accordance with applicable standards if hot spot is observed at any point in the casting, it is rejected.

(7) Range of temperature gradient and cooling rate observed in the areas wherein defects were found after application of MDF criteria, hot spot (solidification time), hot spot (Ciritical Fraction Solid Point (CFS)), are recorded. The same in the areas where defects were not observed are also recorded. In case of models where defects are not observed these ranges have been recorded for the full volume.

(8) Yield of casting: The yield of casting has been calculated as follows:

$$\text{Yield (in \%)} = \frac{V_{cgr} - V_c}{V_c} \times 100$$

V_{cgr} = Volume of casting with runner and gate.

V_c = Volume of casting

(9) Acceptance status: After application of MDF and hot spot criteria, if any defects are observed those models have been rejected and others are accepted.

The following results were analyzed.

1) The variation of maximum casting temperature, minimum casting temperature, maximum mould temperature and minimum mould temperature with respect to time in seconds.

2) The variation of difference between the maximum and minimum casting temperature with respect to time in seconds.

3) The variation of time derivative of maximum casting temperature and minimum casting temperature with respect to time in seconds.

The post simulation results such as observations related to MDF and Hot spots, temperature gradient and cooling rate observed at locations where defects were observed and defects were not observed, peak value, time of reach 150° C and time to reach peak value of difference of maximum and minimum casting temperature, initial range (during ascending period) and time to reach peak value of time derivative, CFS at Niyama point and yield, were recorded. The variation of temperature difference of maximum and minimum casting temperature and time derivative of minimum casting temperature are indications of availability of temperature gradient in the casting. These results are given in Table 2.

Model#	ACCEPTANCE CRITERIA			RESULTS	TEMP GRADIENT (°C/cm)		COOLING RATE (°C/second)		TEMPERATURE DIFFERENCE (°C)			TIME DERIVATIVE OF MIN CASTING TEMP. (°C/sec)		CFS AT NIYAMA Point	YELD
	MDF	HOTSPOTS	CFS		Defect Area	Defect Free Area	Defect Area	Defect Free Area	Peak value (°C/sec)	Time to reach 150°C (sec)	Time to reach Peak (°C/sec)	Initial range	Time to reach Peak (°C/sec)		
1.1	No	Yes	Yes	Rejected	8	10 to 15	175	>175 <175	390	10	46	10 to 25	8	Un-favourable	32%
1.2	Yes	No	No	Rejected	9	10 to 25	320	>320 <320	400	11	30	10 to 55	1001	Un-favourable	32%
1.3	Yes	No	Yes(thin)	Rejected	8	10 to 25	320	>320 <320	480	10	30	5 to 145	10	Un-favourable	32%
1.4	Yes	No	Yes(thin)	Rejected	8	10 to 25	320	>320 <320	400	10	30	10 to 25	12	Un-favourable	32%
2.1	Yes	No	No	Rejected	8	10 to 25	.	>320 <320	400	19	40	10 to 25	12	Un-favourable	35%
2.2	No	No	No	Accepted	..	47.785	340	1148- 1288	325	55	45	10 to 25	12	Favourable	35%
2.3	Yes	No	No	Rejected	7	10 to 25	320	>340 <340	400	10	30	10 to 26	12	Un-favourable	35%
2.4	Yes	No	No	Rejected	7.5	10 to 25	320	>330 <330	480	20	30	0 to 250	12	Un-favourable	35%
3.1	Yes	No	No	Rejected	8	10 to 25	320	>320 <320	400	10	21	10 to 30	10	Un-favourable	35%
3.2	Yes	No	No	Rejected	7	10 to 25	320	>320 <320	480	8	31	3 to 150	10	Un-favourable	35%
3.3	Yes	No	No	Rejected	7	10 to 25	320	>320 <320	400	10	40	10 to 55	12	Un-favourable	35%
3.4	Yes	No	No	Rejected	8	10 to 25	315	>315 <315	425	10	26	7.5 to 25	10	Un-favourable	35%

Table 2 – POST SIMULATION RESULTS

8. DISCUSSION ON RESULTS.

Since the geometry of the mould remains same except for the change in the draft provided, the heat transfer at outer mould surface, the heat transfer from liquid to solid phase remain unaltered among the models. But the number of gates influence the heat transfer between the casting – mould as the area of interface in a given time will be more in case of more number of gates, which can be seen from the observations.

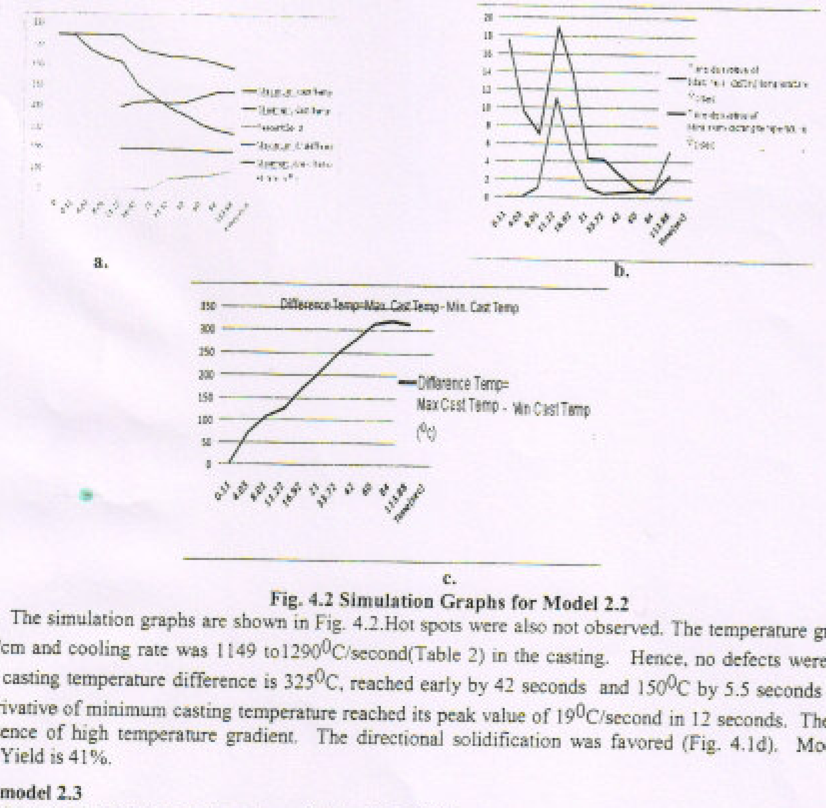
With increase in number of gates, the minimum casting temperature, temperature difference between maximum and minimum casting temperature increase. Since the location of gates (in case of more than one) is symmetric, it can be seen that the heat transfer is more uniform besides being faster. Hence, the better results are obtained in case of two or three gates. It can also be seen that in case of number of gates provided is two or three, no hot spots are observed except in case of model 2.3. When the number of gates remain same change in the runner of cross section is affected the results are observed to differ marginally, where the height of cross section is kept 2mm, the minimum casting temperature increases at a marginally faster rate, which can be attributed to the better flow of molten material. The draft angle, when increased from 0.25degree to 0.5 degree keeping number of gates and runner cross section same, the heat transfer is observed marginally faster as the surface area increases. As illustration, the discussions on result of following two models are placed here.

8.1 FOR MODEL 2.2.

Model 2.2 has a two gate system (Table 1). Solidification has been completed in 1.7509 minutes. The iso-surfaces for MDF (Fig. 4.1a), Hotspot (Solidification time) (Fig. 4.1b), Hotspot (Critical Fraction Solid time) (Fig. 4.1c), Critical Fraction solid time at Niyama criteria (Fig. 3.1d) are given. In this case, MDF less than 0.999 was not observed. Hot spots were also not observed.

a. Material Density **b. Hot Spot (Solidification Time)** **c. Hot Spot (Cfs)** **d. Cfs**

Fig. 4.1 Iso-surface Pictures for Model 2.2



a.

b.

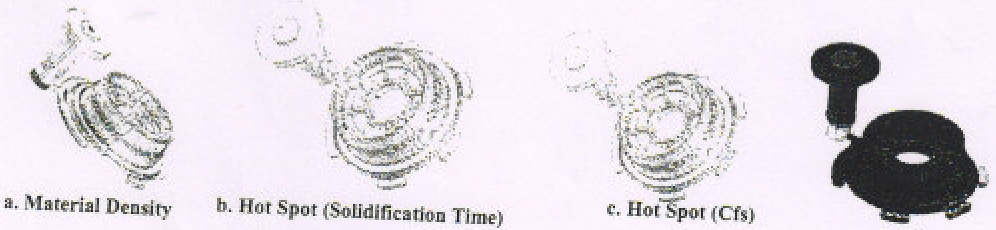
c.

Fig. 4.2 Simulation Graphs for Model 2.2

The simulation graphs are shown in Fig. 4.2.Hot spots were also not observed. The temperature gradient was 47 – 79.5^{0}C/cm and cooling rate was 1149 to1290^{0}C/second(Table 2) in the casting. Hence, no defects were observed. The peak of casting temperature difference is 325^{0}C, reached early by 42 seconds and 150^{0}C by 5.5 seconds (Fig. 4.2c). The time derivative of minimum casting temperature reached its peak value of 19^{0}C/second in 12 seconds. These also indicate the presence of high temperature gradient. The directional solidification was favored (Fig. 4.1d). Model is accepted. Casting Yield is 41%.

8.2 For model 2.3

Model 2.3 has a two gate system (Table 1). Solidification has been completed in 1.5715 minutes. The iso-surfaces for MDF (Fig 4.3a), Hotspot (Solidification time) (Fig. 4.3b), Hotspot (Critical Fraction Solid time) (Fig. 4.3c), Critical Fraction solid time at Niyama criteria (Fig 4.3d), are given. In this case, MDF Less than 0.999 was observed at the bottom ,near sprue gate (Fig. 4.3a) and hot spots were not observed (Fig. 4.3b & c).



a. Material Density b. Hot Spot (Solidification Time) c. Hot Spot (Cfs) d. Cfs

Fig. 4.3 Iso-surface Pictures for Model 2.3

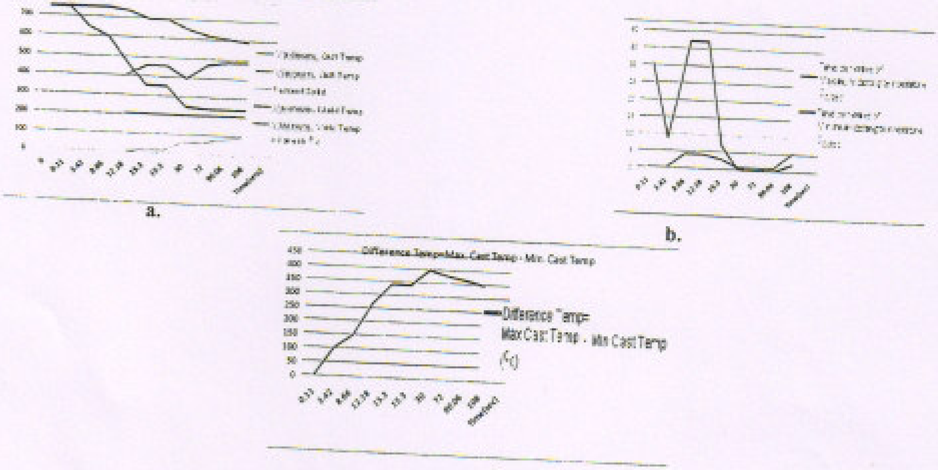


Fig. 4.4 Simulation Graphs for Model 2.3

The simulation graphs are shown in Fig. 4.4.The temperature gradient and cooling rate were observed as 7^{0}C/cm and 340^{0}C/minute respectively (Table 2). The casting temperature difference rising to 150^{0}C in 10 seconds, its peak value of 400^{0}C in 30 seconds(Fig. 4.4c), the time derivative of minimum casting temperature rising from 9 to 37^{0}C/second in twelve seconds (Fig .4.4b), indicate the presence of low temperature gradient. The low temperature gradient together with moderately high cooling rate near the entrance of mould, resulted in defects. The directional solidification was not favored (Fig. 3.3d). The model is rejected.

9. CONCLUSSION:

There are 12 models for nose wheel half hub casting which have been tried out through simulation, out of which model 2.2 having two gates is accepted as it satisfies all criteria while 11 are rejected (Table 2). In case of model 2.2, the spatial temperature gradient and cooling rate are observed to be in the range of 47 to 79.5° C/cm and 1149 to 1290° C/min respectively, which implies presence of high temperature gradient and high cooling rate that resulted into a defect free casting. Hence this design is recommended.

10. RECOMMENDATIONS

From Table 2, the favorable and unfavorable ranges for temperature gradient and the cooling rate can be inferred as following

Unfavorable range for		Favorable range for	
Temperature gradient (°C/cm)	Cooling rate (°C/min)	Temperature gradient (°C/cm)	Cooling rate (°C/min)
7 to 8	315 to 340	47 – 79.5	1149 to 1290

Hence, it can be concluded that a temperature gradient above 47° C/cm and cooling rate above 1150 ° C/cm would produce defect free castings in these cases.

Two gate feeder system is found to be adequate to dissipate heat.

REFERENCES

[1] *Sirrel, B., Holliday, M and Cambell, J., 1995 "Modeling of Casting, Welding and Advanced Solidification Processes" (MCWASP VII) London, 1995, pp 913 - 933.*

[2] *Jain, N., Carleson, K D and Backermann, C., 2007, "Round Robin study to assess variations in casting simulation Niyama Criterion Predictions", Proceedings of 61^{st} SFSA Technical & Operating conference, Paper No.5.5, Steel Foundry's Society of America, Chicago, IL, 2007.*

[3] *Li, Hai Peng., Liang, Chun Yong., Wang, Li Hui and Wang, Hong Shui., 2011,* "Numerical Simulation of Casting Process for Gray Iron Butterfly Valve", *Advanced Materials Research, pp 189-193, 260, February 2011. Available on line at Scientific.net.*

[4] *Couturier, G and Rappaz, M., 2006, "Modeling of porosity formation in multi component alloys in the presence of several dissolved gases and volatile solute elements" TMS symposium on simulation of Aluminum shape casting process (2006).*

[5] *Hirt, C.W., 2011, "Predicting Core Shooting, Drying and Defect Development", Foundry Management & Technology, January 2011.*

[6] *Chandra, V., 1995, "Computer prediction of hot tears, hot cracks, residual stresses and distortions in precision castings. Basic concepts and approach", Proc.124 TMS Annual meeting, Warandale PA, pp 107-117.*

[7] *Dominique, Lefebrrve., Alfons, Maekenbrock., Valerie, Vidal., Vincent, Pavan and Pieter, Haigh M., 2004, "Development and use of simulation in the design of blown cores and moulds" World Foundry Congress 2004, Turkey.*

[8] *Reikher, A., Gerber, H., Pillai, K M and Jen T C., 2010, "Natural Convection—An Overlooked Phenomenon of the Solidification Process", Die Casting Engineer, January 2010.*

[9] *Sirvio, M and Wos, M.,* "Casting directly from a computer model by using advanced simulation software, *FLOW-3D Cast," Archives of Foundry Engineering Volume 9, Issue 1/2009, pp 79-82.*

[10] *Ngadia, Taha Niane and Michalet, Jean-Pierre., 2011, "Validation of Foundry Process for Aluminum Parts with FLOW-3D Software", Proceedings of the 2011 International Symposium on Liquid Metal Processing and Casting, 2011.*