Semi-automated Gating System Design with Optimum Gate and Overflow Positions for Aluminum HPDC

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Abstract Die casters usually carry out a die casting test before producing new castings. At the die-casting test stage, the runner and gate parts are always repeatedly corrected, which lead to a lengthened processing time and increased processing cost. In this study, a computer software was developed to calculate the gating system design with optimum gate and overflow positions for cold chamber High Pressure Die Casting (HPDC) die design by getting the part dimensions and choosing the suitable machine from a pre-defined database in the software. A design of experiment is used to formulate the objective function of the gate and overflow optimum position. At the end of this paper, a case study was developed as part of the software validation. The results show that the developed software can calculate the gating system design and eliminate the correction in the test stage.

Keywords HPDC · Die casting · Gating system · Die casting design

1 Introduction

Die-casting is similar to permanent mold casting except that the metal is injected into the mold under a high pressure of 10–210 MPa (equiv. to 1450–30,500 psi). This results in a more uniform part with a generally good surface finish and good dimensional accuracy, as well as 0.2% of the casting dimension. For many parts, post-machining can be totally eliminated, or very light machining may be required to bring dimensions to size.

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However, because of the high injection speed, die-casters usually carry out a die-casting test before producing new castings to eliminate part defects. In this stage the runner and gate parts are always repeatedly correctly, which leads to a lengthened processing time and increased processing cost.

In this area, some researches study the gating system only, while others only study the runner system and its effects of product defects. In this research developing a software, using visual basic that give a recommended gate and runner design (Gating system) related to the product's dimensions and machine used. This will minimize the part defects/porosity. Moreover, the software lets the user choose from the different machines and its plunger diameter from a pre-defined database to get a desired number of cavities for the user's case.

Mentioned, some researches only study the runner system, such as Tai and Lin [15] which use a simulated annealing optimization algorithm with a performance index to get the optimum runner network. Weishan et al. [17] developed a CAD/CAE system for die casting. By using the CAD package, die designers can determine the location, the shape and the dimension of the runner and gating systems of die castings according to the characteristics of the die-casting machine, the geometry of the casting, and the properties of the alloy. Through the interactive process of CAD/CAE, and an ideal design can be provided with the best filling pattern and the optimal thermal conditions for both the die and the die casting. Lee and Lu [11] proposed a new mathematical model for the calculation of the back pressure in a die cavity. Fuh et al. [3] described a prototype system structured by several functional modules as specific add-on applications on a commercial CAD system for die casting die design. These modules include data initialization, cavity layout, gating system design, die-base, parting, standard components design, among others. The focus of the development was placed on gating, runner and die-based design. Yue et al. [19] established a CAD/CAE/CAM integrated system dies for application in the primary stage. The use of this integrated system can shorten the cycle of die design and manufacturing, as the lead-time of die castings is shortened greatly. Shehata and Abd-Elhamid [14] presented main die designing procedures and related equations in logical way. A computer program is developed to estimate the main die elements based on the geometry input of casting shape. After the initial inputs given, the system does full calculations, optimizes selections, and lists main die element sizes. The program can present die characteristics and casting machine characteristics. Cleary et al. [2] explored the effects of die temperature, metal super-heating and volume filling on the short shots for the casting of a simple coaster. The research used simulation methods that proved particularly suited to modeling HPDC is Smoothed Particle Hydrodynamics (SPH). SPH was used to study three industrial case studies. Hangai and Kitahara [5] proposed a fractal analysis by comparing the porosity in two types of aluminum alloy die casts manufactured by different die-casting processes, and to confirm that the fractal analysis of the spatial distribution of pores can quantitatively characterize the porosity. The same researchers [6] proposed another two types of fractional analysis to characterize the porosity in terms of the shape of individual pores and the spatial distribution of multiple pores. Their analysis shown that these are indicators of whether the predominant cause of the porosity is shrinkage or gas. these parameters are expected to indicate the action that should be taken to manufacture pore-free die castings. Park and Yang [12] proposed a linear programming (LP) model that maximizes the average efficiency of processing time for casting in real foundries. Lee et al. [10] presented a methodology for obtaining optimal designs of 4-cavity thin electronic component housings. Their study analyzed the fluid behavior and amount of air entrainment caused by the overflows and air vent using a computer fluid dynamics (CFD) simulation. Furthermore, the effect of vacuum systems on the porosity and mechanical properties of the castings was studied in their work. Queudeville et al. [13] modularized a proven instrument in reducing costs in manufacturing processes. Their methodology tries to assist design engineers throughout the development of new dies, helping to choose an appropriate set of modules based on technical as well as economic criteria. Gulagoudar et al. [4] developed a robust design approach to analyze casting defects in foundry. Thus process parameters are set in order to reduce the rejection of castings. Kittur et al. [9] determined the optimal process parameters by using the desirability function. The process parameters, namely, fast shot velocity, injection pressure, phase changeover point, and holding time, have been considered as the input to the model. Porosity, surface roughness, and hardness are measured and represented as the responses. Wu et al. [18] developed a parametric design software for die-casting die gating system, so the designing and modification will be more easy to maintain by using parametric design.

2 Framework of the Gating System

Gating system dimensions directly affect part quality. This requires designer to have detailed information for the part and the machine, so that accurate dimensions for gating system elements as runner, gate overflow and air vent can be achieved, see Fig. 1.

2.1 Part Details/Dimensions

The part details as width, length and height also its thickness and angles, are important to take into account in the designing stage. In this study a standard parallelogram is taken to study the part details with gating system dimensions/details.

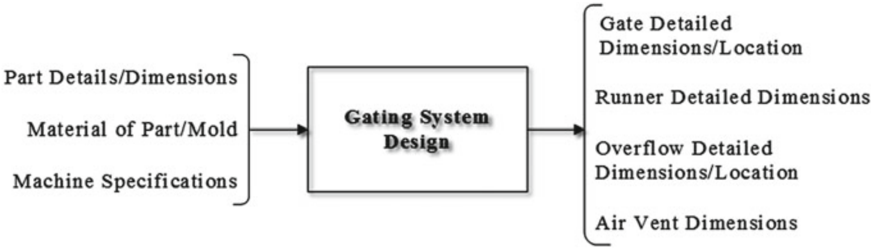

Fig. 1 Gating system design flow chart

2.2 Material of Part/Mold

The material of the part and the mold also affect the design parameters. The study uses the popular part material (Al 306) as seen in Table 1, and also mold material (H13), see Table 2. So designers can cover large variant of part application.

2.3 Machine Specifications

For the material selected, the designer has to follow the specification of the cold chamber HPDC machines. Machine tonnage and casting volume identifies the number of cavities used, also plunger diameter and position affect the runner dimensions and mold design. In this study a pre-defined machine database is created to cover parts details as much as possible. These machines database collected from those in market and compared with many others to be sure that the deviation between machines in the same type almost none see Table 3.

2.4 Gate Detailed Dimensions/Location

"The gate is a narrow opening into the cavity from the gate runner" [18]. Its area is related to casting volume and thickness. The detailed dimensions of the gate can be calculated using functions and rules from handbooks and textbooks ([1], [7], [8], [16]), but the study add experts' reviews to smoothing the gate details for better efficiency. Table 4 show functions used in gate details.

The gate detailed dimensions are given by 8 sections so it can be drawn along the gate path on any CAD modeling software i.e., SolidWorks. Figure 2 shows how sections are drawn with the required smoothness.

The gate location is identified using an experimented model developed using the design obtained by the experimental methods so that the gate location can be related to part dimensions and details.

Table 1 Al 306 (AlSi12) chemical composition

Si %	Fe %	Cu %	Mn %	Mg %	Ni %	Pb %	Sn %	Ti %	Zn %	Al %
10.5–13.5	0.55	0.05	0.35	–	–	–	–	0.15	0.1	Rest

Table 2 H13 1.2344 (X40CrMoV5-1) chemical composition

C %	Si %	Mn %	P %	S %	Cr %	Mo %	V %	Fe %
0.35–0.42	0.8–1.20	0.25–0.50	0.03	0.02	4.80–5.50	1.20–1.50	0.85–1.15	Rest

Table 3 Machines database

Machine/Specs.	Unit	150 TON			250 TON		
Locking force	kN	1500			2500		
Plunger diameter	mm	45	50	60	50	60	70
Injection speed	m/sec	0.1–7.0			0.1–7.0		
Injection force	kN	182			270		
Injection stroke	mm	340			420		
Injection volume	cm^3	362	447	644	540	777	1058
Cast area	cm^2	239/118	296/146	426/210	363/181	524/262	714/357
Machine/Specs.	Unit	420 TON			500 TON		
Locking force	kN	4200			5000		
Plunger diameter	mm	60	70	80	70	80	90
Injection speed	m/sec	0.1–7.0			0.1–7.0		
Injection force	kN	350			520		
Injection stroke	mm	500			630		
Injection volume	cm^3	904	1230	1607	1788	2336	2956
Cast area	cm^2	584/292	794/397	1036/518	919/459	1201/599	1522/775
Machine/Specs.	Unit	650 TON			Machines database		
Locking force	kN	6500					
Plunger diameter	mm	70	80	90			
Injection speed	m/sec	0.1–7.0					
Injection force	kN	545					
Injection stroke	mm	630					
Injection volume	cm^3	1788	2336	2956			
Cast area	cm^2	919/459	1201/599	1522/775			

2.5 Runner Detailed Dimensions

Runner is responsible to feed the gates from the machine sleeve. It is composed of the main runner and branch runners. Branch runners are connected to the main runner and the part, its cross sectional area is equal to that of the gate at Sect. 8. The main runner has a different cross sectional area, depending on the branch runners connected. For every two branches runners connected the main runner area must be more than 1.1 times the sum of their areas.

2.6 Overflow Detailed Dimensions/Location

The overflow is a volume of aluminum that is responsible for reducing non-metallic inclusions (porosity) and air entrapment, localized after the part. The size of the

Table 4 Gating system equations

Equation	Parameters
$t = k\left[\frac{T_i - T_f + S\cdot Z}{T_f - T_d}\right]T$[16]	k = Empirically derived constant related to the die steel T = Wall thickness (mm) t = Max. filling time (sec) T_f = Min. flow temperature of the metal alloy (°C) T_i = Metal temperature at the ingate (°C) T_d = Die surface temperature just before the metal arrives (°C) S = Percent solids at the end of fill Z = Solids units conversion factor, degree to %
$Q_i = \frac{V_i}{t}$	Q_i = Flow rate of a segment (mm^3/sec) V_i = Volume of a segment volume (mm^3) t = Cavity filling time (sec)
$A_{appi} = \frac{Q_i}{v_g}$	A_{appi} = Apparent ingate area of a segment (mm^2) Q_i = Flow rate of a segment volume (mm^3) v_g = Ingate velocity (mm/sec)
$v^{\mathbf{1.71}} \cdot T_g \cdot \rho \geq J$	v_g = The ingate velocity (mm/sec) T_g = The ingate thickness (mm) ρ = The density of the metal (N/mm^3) J = The atomization factor
$A_v = \frac{A_{gapp}}{4}$[16]	A_v = The min. area of the vent (mm^2) A_{gapp} = Apparent area of the ingate (mm^2)
$V_c = \left(V_p + V_o\right) \cdot 1.2$	V_c = Cast volume (mm^3) V_p = Part volume (mm^3) V_o = Overflow volume (mm^3)
$A_c = A_p \cdot 1.5$	A_c = Cast projected area (mm^2) A_p = Part projected area (mm^2)

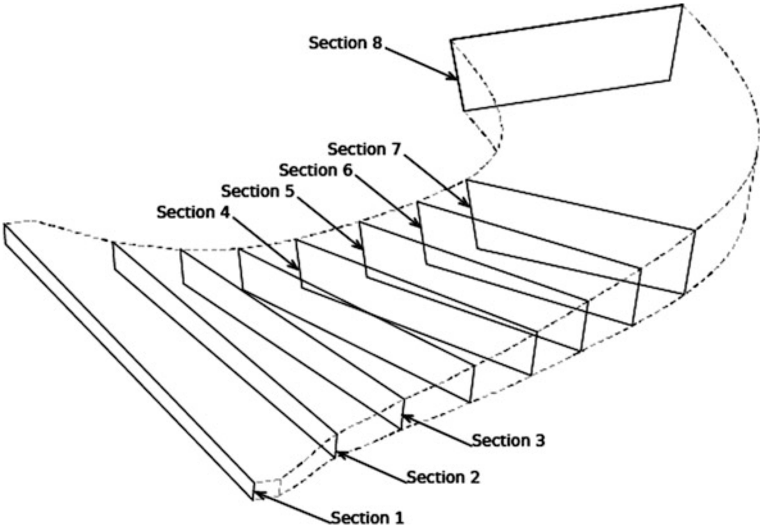

Fig. 2 Gate detailed sections

overflow is depending on the part volume and thickness. The rule of overflow volume selection was implemented by the IF/THEN rule. Overflow location is identified via the same experimental model used for gate location.

2.7 *Air Vent Dimensions*

Air vent is just a narrow area that enables air to escape without letting aluminum out. It helps the air entrapment of the gating system. Its area can be calculated from the gate area Table 4.

3 Experimental Model

The study developed an experimental model to study the effect of the part factors on the its porosity. Also creates an objective function for porosity percentage so it can minimize. These factors are related to part dimensions i.e., Width, length, height, angle and thickness. Furthermore, there are two factors that have been created to study gate and overflow positions effect. GSS (Gate Shift Scale) and OSS (Overflow Shift Scale) are the factors responsible for gate and overflow positions, see Fig. 3.

The study used Box-Behnken experimental design to study the effect of the factors Table 5 on the porosity percentage. A simulation model was developed for

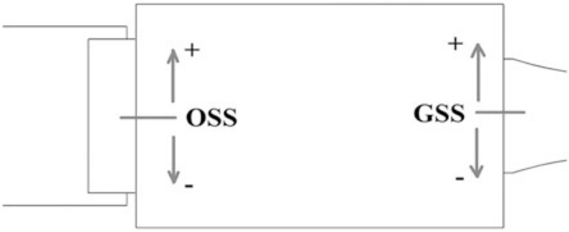

Fig. 3 GSS and OSS factors

Table 5 Box-Behnken design factors

#	Factor	Description	Units	Range	
				From	To
1.	Width	Part width	mm	20	200
2.	Length	Part length	mm	25	250
3.	Height	Part height	mm	10	100
4.	Angle	Part angle	degree	50	90
5.	Thickness	Part thickness	mm	0.3	3
6.	GSS	Gate shift scale	ul	−1	1
7.	OSS	Overflow shift scale	ul	−1	1

Table 6 Simulation model parameters

Parameter	Units	Value
Atmospheric temperature	°C	35
Die temperature	°C	280
Molten aluminum temperature	°C	650
Incoming velocity	m/sec	1

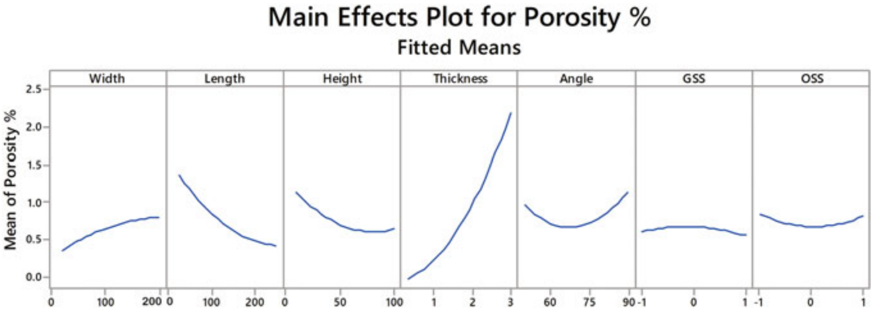

Fig. 4 Main effects plot for porosity %

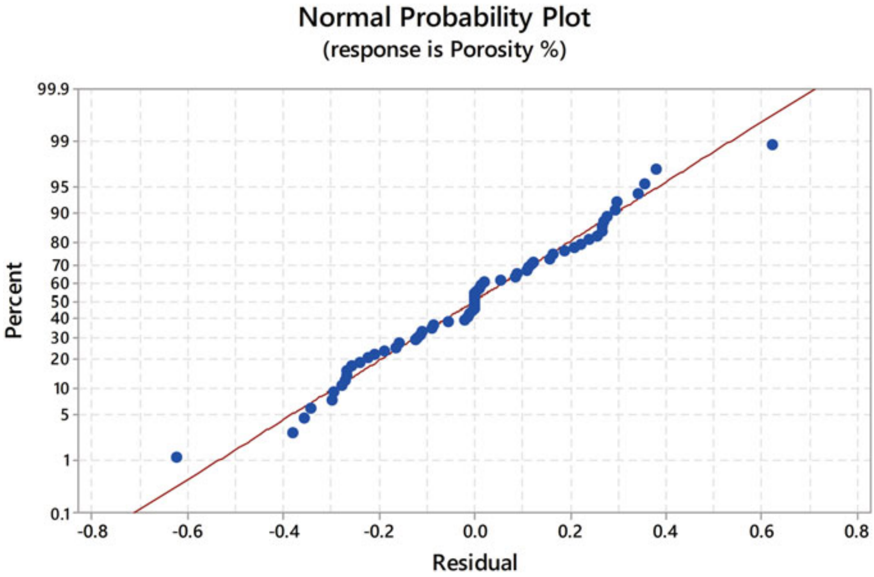

Fig. 5 Normal probability plot

this experiment using ProCAST[1] software. To study the effect of the 7 factors only the other parameters must be fixed, Table 4 shows simulation parameters used (Table 6).

The experiment shows how the porosity affected from the part shape specially the thickness and also that GSS and OSS affect it, see Fig. 4. The experiment also built a model that described the effect of all the seven factors on the porosity percentage, see Fig. 5. Once the all 5 factors are known from equations from handbooks and experts' reviews it will be easy to get the values of GSS and OSS that gets the minimum porosity for the chosen part, see Eq. (1).

Equation (1)—*Describes the relation between Width, Length, Thickness, Angle, GSS and OSS factors and the part Porosity % as an output from the experimental design*

$$\begin{aligned}\text{Porosity}\,\% = {} & 5.75 - 0.00009 \cdot \mathit{Width} - 0.00953 \cdot \mathit{Length} - 0.0195 \cdot \mathit{Height} + 0.208 \\ & \cdot \mathit{Thickness} - 0.1313 \cdot \mathit{Angle} - 0.327 \cdot \mathit{GSS} - 0.456 \cdot \mathit{OSS} - 0.000012 \\ & \cdot \mathit{Width}^2 + 0.000017 \cdot \mathit{Length}^2 + 0.000106 \cdot \mathit{Height}^2 + 0.2283 \\ & \cdot \mathit{Thickness}^2 + 0.000946 \cdot \mathit{Angle}^2 - 0.0934 \cdot \mathit{GSS}^2 + 0.1598 \cdot \mathit{OSS}^2 \\ & + 0.000028 \cdot \mathit{Width} \cdot \mathit{Length} - 0.000068 \cdot \mathit{Width} \cdot \mathit{Height} + 0.0017 \mathit{Width} \\ & \cdot \mathit{Thickness} + 0.000031 \cdot \mathit{Width} \cdot \mathit{Angle} - 0.00003 \cdot \mathit{Width} \cdot \mathit{GSS} \\ & + 0.00008 \cdot \mathit{Width} \cdot \mathit{OSS} + 0.000058 \cdot \mathit{Length} \cdot \mathit{Height} - 0.002092 \\ & \cdot \mathit{Length} \cdot \mathit{Thickness} - 0.000031 \cdot \mathit{Length} \cdot \mathit{Angle} + 0.00077 \cdot \mathit{Length} \\ & \cdot \mathit{GSS} + 0.00072 \cdot \mathit{Length} \cdot \mathit{OSS} - 0.00148 \cdot \mathit{Height} \cdot \mathit{Thickness} \\ & + 0.000064 \cdot \mathit{Height} \cdot \mathit{Angle} + 0.00179 \cdot \mathit{Height} \cdot \mathit{GSS} + 0.00015 \\ & \cdot \mathit{Height} \cdot \mathit{OSS} + 0.00053 \cdot \mathit{Thickess} \cdot \mathit{Angle} + 0.0020 \mathit{Thicknes} \cdot \mathit{GSS} \\ & + 0.0191 \cdot \mathit{Thickness} \cdot \mathit{OSS} + 0.00136 \cdot \mathit{Angle} \cdot \mathit{GSS}\end{aligned} \tag{1}$$

4 Validation

The study validating of the developed software and the model output was performed by creating two HPDC aluminum dies designs. The part dimensions in the two models are the same but the first model has one cavity and the other has two cavities. The validation uses two methods, first by ProCAST simulation software and the other by built the mold itself with all its stages, beginning from full design using SolidWorks CAD software through manufacturing and injection on cold chamber HPDC machine.

The software is developed to be as simple as possible to meet user needs. The following steps are the steps used in the software:

1. The user inputs the dimensions and the thickness of the shape as shown in Fig. 6.

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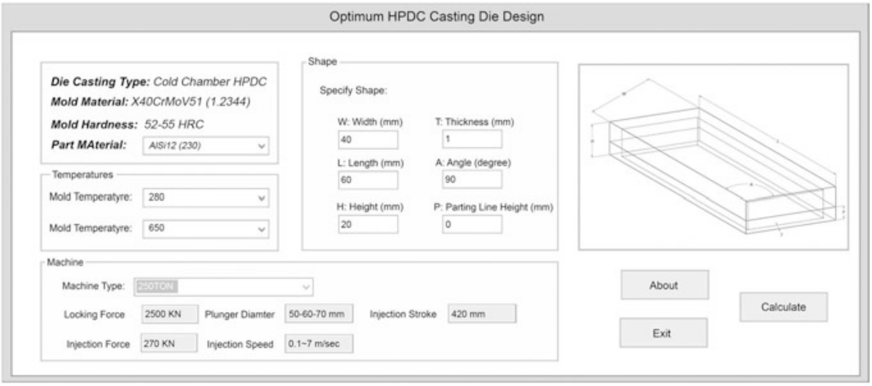
[1] ProCAST: is software used for foundry simulation for all casting processes.



Die Casting Type: *Cold Chamber HPDC*
Mold Material: *X40CrMoV51 (1.2344)*
Mold Hardness: *52-55 HRC*
Part MAterial: *AlSi12 (230)*

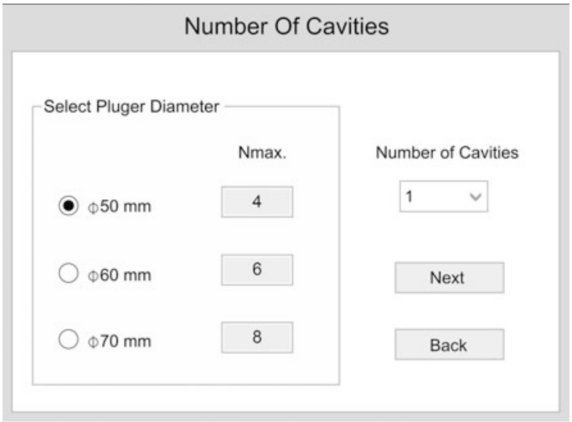
Mold Temperatyre: 280
Mold Temperatyre: 650

Specify Shape:
W: Width (mm) 40
T: Thickness (mm) 1
L: Length (mm) 60
A: Angle (degree) 90
H: Height (mm) 20
P: Parting Line Height (mm) 0

Machine Type: 250TON
Locking Force 2500 KN
Plunger Diamter 50-60-70 mm
Injection Stroke 420 mm
Injection Force 270 KN
Injection Speed 0.1~7 m/sec

Fig. 6 User input

2. The user also selects the type of machine and temperature used for his application.
3. The software calculates from the data input and machine database the maximum number of cavities can be used in this die design. It is calculated from the minimum number of cavities gets from the maximum number of cavities calculated from the machine volume, machine plunger speed and machine locking force.
4. User again chooses the plunger and selects the number of cavities needed or presses back to select another machine if this machine not suitable for his application as in Fig. 7.
5. The software calculates the plunger speed of the machine as an output for the user.
6. It also calculates the gate area and dimensions with all its sections.

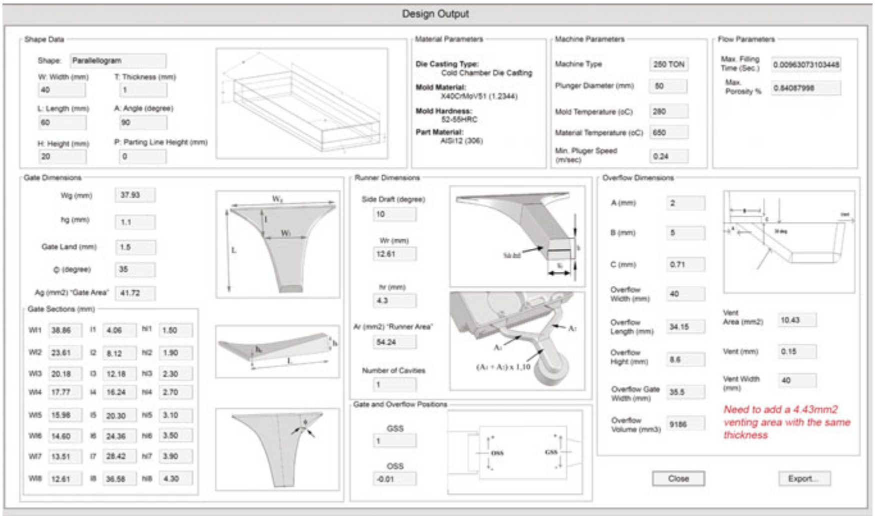


	Nmax.
● ϕ50 mm	4
○ ϕ60 mm	6
○ ϕ70 mm	8

Number of Cavities: 1

Fig. 7 Number of cavities

7. Moreover, the software calculates the overflow and vent area with detailed dimensions.
8. Finally, it calculates the optimum gate and overflow positions.
9. After these calculations, the software gives the output calculations with a simple form as viewed in Fig. 8.



Shape Data

Shape: Parallelogram
W: Width (mm): 40
T: Thickness (mm): 1
L: Length (mm): 60
A: Angle (degree): 90
H: Height (mm): 20
P: Parting Line Height (mm): 0

Material Parameters

Die Casting Type: Cold Chamber Die Casting
Mold Material: X40CrMoV51 (1.2344)
Mold Hardness: 52-55HRC
Part Material: AISi12 (306)

Machine Parameters

Machine Type: 250 TON
Plunger Diameter (mm): 50
Mold Temperature (oC): 280
Material Temperature (oC): 650
Min. Pluger Speed (m/sec): 0.24

Flow Parameters

Max. Filling Time (Sec.): 0.00963073103448
Max. Porosity %: 0.84087998

Gate Dimensions

Wg (mm): 37.93
hg (mm): 1.1
Gate Land (mm): 1.5
Ф (degree): 35
Ag (mm2) "Gate Area": 41.72

Gate Sections (mm)

Wl1	38.86	l1	4.06	hl1	1.50
Wl2	23.61	l2	8.12	hl2	1.90
Wl3	20.18	l3	12.18	hl3	2.30
Wl4	17.77	l4	16.24	hl4	2.70
Wl5	15.98	l5	20.30	hl5	3.10
Wl6	14.60	l6	24.36	hl6	3.50
Wl7	13.51	l7	28.42	hl7	3.90
Wl8	12.61	l8	36.58	hl8	4.30

Runner Dimensions

Side Draft (degree): 10
Wr (mm): 12.61
hr (mm): 4.3
Ar (mm2) "Runner Area": 54.24
Number of Cavities: 1

Gate and Overflow Positions

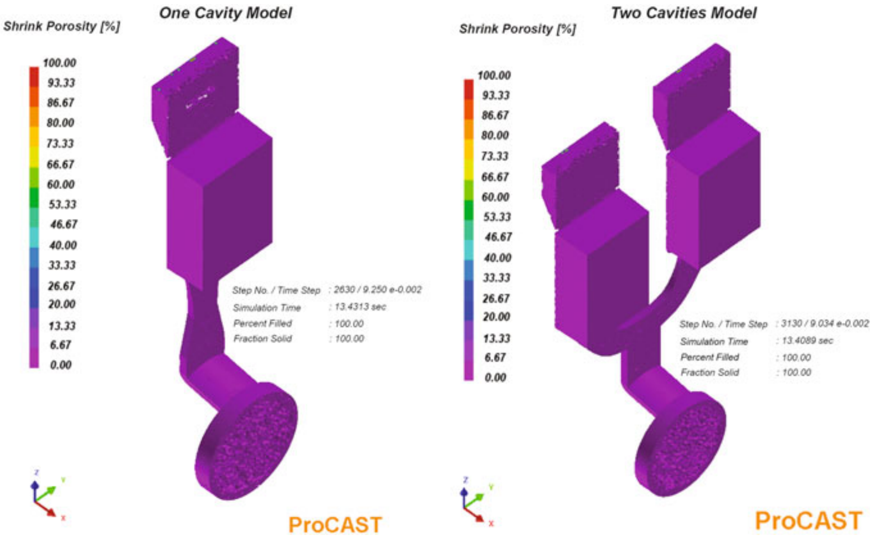
GSS: 1
OSS: -0.01

Overflow Dimensions

A (mm): 2
B (mm): 5
C (mm): 0.71
Overflow Width (mm): 40
Overflow Length (mm): 34.15
Overflow Hight (mm): 8.6
Overflow Gate Width (mm): 35.5
Overflow Volume (mm3): 9186
Vent Area (mm2): 10.43
Vent (mm): 0.15
Vent Width (mm): 40

Need to add a 4.43mm2 venting area with the same thickness

Fig. 8 Design output



Step No. / Time Step : 2630 / 9.250 e-0.002
Simulation Time : 13.4313 sec
Percent Filled : 100.00
Fraction Solid : 100.00

Step No. / Time Step : 3130 / 9.034 e-0.002
Simulation Time : 13.4089 sec
Percent Filled : 100.00
Fraction Solid : 100.00

Fig. 9 The two ProCAST validation models, one cavity model on the *left* and two cavities model on the *right*

In Fig. 8 the developed software gives that the maximum porosity of 0.8% with this design. And that was the same results obtained from ProCAST simulation model in Fig. 9.

The other validation for the developed software is done by manufacture two molds. Figure 10 shows the design of the two molds. Figure 11 shows the 2 molds after manufacturing.

After manufacturing the molds, it has been tested on a HPDC cold chamber machine 250TON. Figure 12 presents validation parts after testing the molds on the HPDC machine.

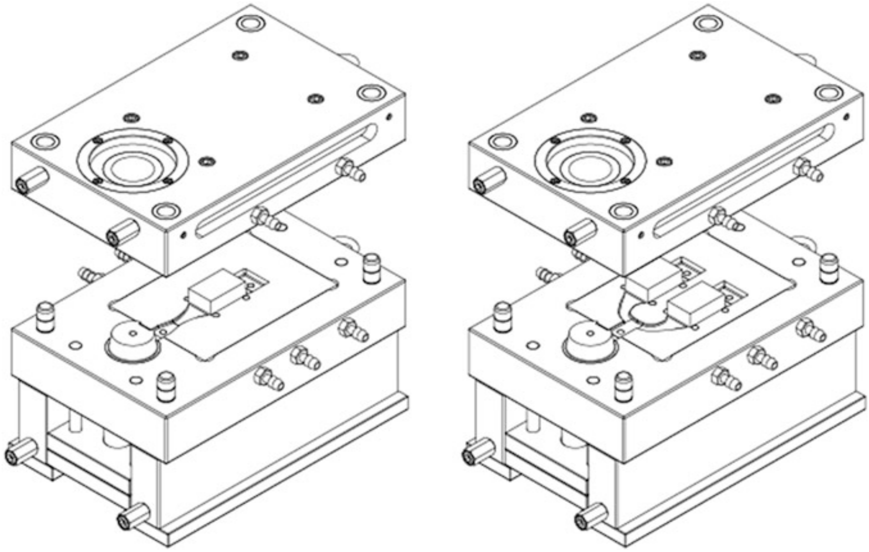


Fig. 10 The two validation molds design, one cavity model on the *left* and two cavities model on the *right*

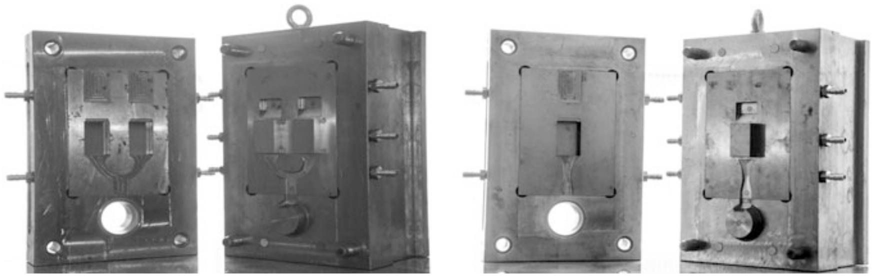


Fig. 11 The two validation molds after manufacturing, one cavity model on the *right* and two cavities model on the *left*

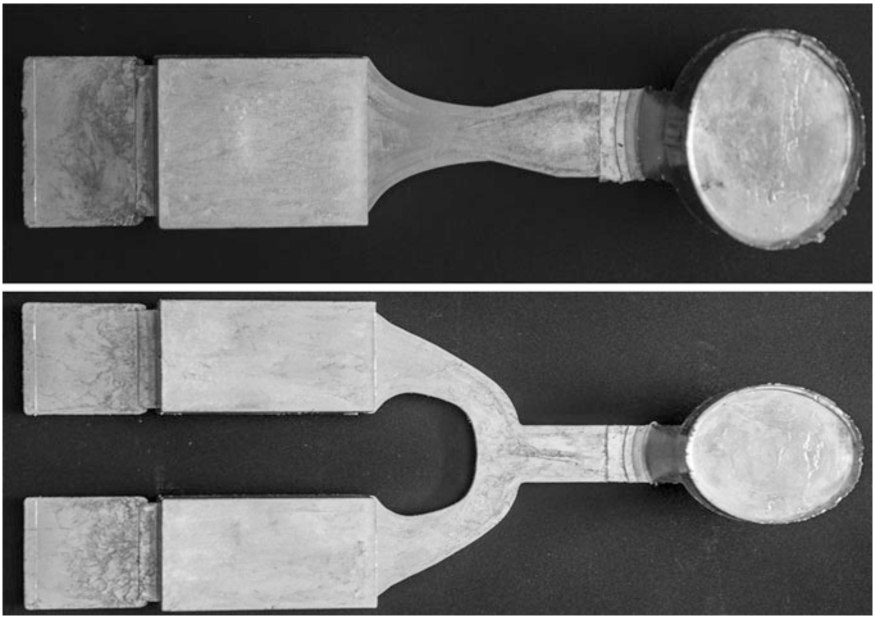


Fig. 12 The two validation parts, one cavity validation model on the *top* and two cavities validation model on *bottom*

The components have been sectioned in random sections to show if there is any porosity in the component or not. Figure 13 shows that there is no porosity in the components even after polishing the sectioned surface.

5 Discussions and Conclusions

In this work, a computer software has been developed to help cold chamber HPDC die designers by generating a detailed design for the gating system with optimum gate and overflow positions, which traditionally require a long time to design. The software also is validated, which will guarantee the user that the software output eliminates further corrections and adjustments in the gating system testing stage.

The experimental design done in this study gives an equation to relate all the 7 factors to the porosity percentage, it also concludes the following:

1. Part thickness is the most effective parameter for part porosity %.
2. The best gate location is to be shifted to the right side of the part (GSS = 1), regardless to all parallelogram parameters including its angle.
3. Also the best location for the overflow is around the center depending on the angle of the part.

Fig. 13 Part sections with no porosity, polished section on *bottom* and without polishing on *top*

This study recommends the following:

1. Extend the study to cover the injection process with its factors.
2. Study more complex shapes.
3. Make the cooling rate and its parameters a part of the model.

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