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Analysis and Optimisation of High Pressure Die Casting Parameters to Achieve Six Sigma Quality Product Using Numerical Simulation Approach

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ABSTRACT

A numerical simulation approach is proposed to predict the optimal parameter setting during high pressure die casting. The contribution from the optimal parameters, the temperature, showed more influence on the casting quality than the other parameters. This study's outcome was beneficial for finding the solution for casting defects that occurs due to incorrect setting of process parameters in die casting. Thus, a combination of numerical optimisation techniques and casting simulation serves as a tool to improve the casting product quality in die casting industries. This paper aims to analyse and optimise critical parameters like injection pressure, molten metal temperature, holding time, and plunger velocity, contributing to the defects. In this research paper, an effort has been made to give optimal pressure, temperature, holding time, and plunger velocity parameters using ProCAST simulation software that uses finite element analysis technology. Numerical analysis for optimising the parameters by varying the temperature of molten metal, injection pressure, holding time, and plunger velocity, concerning solidification time at hot spots, is an essential parameter for studying the defect analysis in the simulated model.

Keywords— High Pressure Die Casting (HPDC), Parameters, ProCAST, Simulation, Six Sigma Quality

I. INTRODUCTION

Die casting processes to suffer from poor quality and productivity due to the involvement of a process parameter; hence as per, Mohanty and Jena (2014), one has to control the process parameter to achieve zero-defect parts. The rejection level in the die casting process was found to be 11 to 13 per cent. The reason for this rejection is a blowhole, insufficient injection pressure, improper filling time, porosities, and hot spots. For controlling the process parameter, one must know the effect of process parameters on casting and their influence on defects. The present investigations die cast rotor component and two cross-sections, one at molten entry into the gating system and other at the bottom section, as shown in Figure 1.

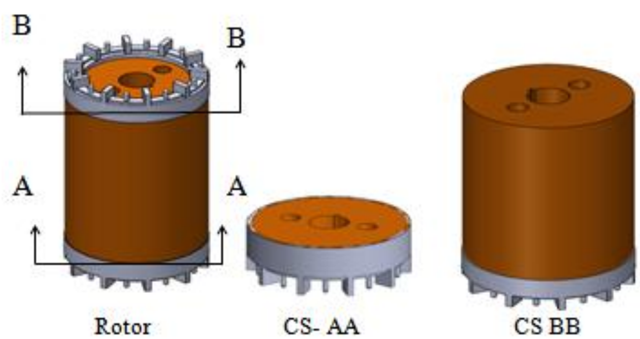

Figure 1: Die casting rotor component and cs at AA and BB for numerical analysis

II. PROCESS PARAMETERS AFFECTING HIGH PRESSURE DIE CASTING

The heat cycle process on vertical high pressure die casting of rotor component with completion time, as shown in Figure 2 and time required for each stage is represented in Table 1. (Data from Crompton Greaves Ltd, (CGL), Motor division, Kundaim Goa).

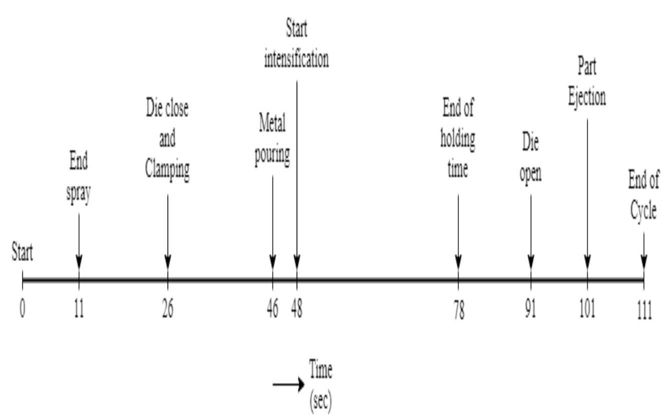

Figure 2: Die casting heat process cycle represented on a timeline in seconds (Industrial case-CGL)

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Table 1: Heat cycle time at various stages of the die casting process

Event	Time (Sec)
Die coat spray	11
Die closing and clamping	15
Molten metal pouring	20
Injection of molten metal	02
From injection to just before die opening(Holding time)	30
Die opening	13
Part ejection	10
Die visual inspection	10

For the investigation of process parameters, the process has been studied over an entire casting cycle on a vertical die casting machine of capacity 100 Tons, as shown in Figure 3.

Figure 3: Experimentation setup: vertical die casting machine of the capacity of 100 Tons (Industrial case-CGL)

A) High Pressure Die Casting Process Parameters

High pressure die casting (HPDC) is affected by the fundamental technological and controllable process parameters. The fundamental technological parameters such as plunger velocity, pressure, filling time, and temperature of the mould and the main controlled variables are metal temperature, slow and quick shot, intensification pressure, die holding time, and the metal's chemical composition.

B) Molten Metal Temperature

Pouring molten metal temperature generally varies from 650 to 800 degrees Celsius, given by Domkin, K. et al. (2009). The fluidity is entirely dependent upon molten metal temperature. Generally, a better fluidity in higher temperatures connected with the viscosity and surface tension of molten metal, which leads to the increasing filling rate. Simultaneously, the heat volume of molten alloy rises with increasing the pouring temperature, which increases of filling time. As per, Lattanzi, L. et al., (2017) the pouring temperature also affects the microstructure development significantly and affects the final structure and toughness of casting product.

C) Preheat Temperature

Preheating in the pressure die casting is done to remove the possibility of the formation of temperature gradients. A significant requirement for producing the right quality castings product is retaining an optimum temperature of the mould cavity surface's parts.

D) Injection Pressure

The pressure causes the metal material to flow, die clamping, platen holding measured by a transducer located in the hydraulic line or the nozzle. Typically, the high pressure and fastest fill rate are the best conditions per Jorstad and Apelian (2009). However, high pressure increase moulded-in stress. The clamping pressure is to keep the mould closed against injection pressure. Therefore, based on Zhang, M. et al. (2008), the amount of clamp pressure required based on the moulded material.

E) Plunger Velocity

In high pressure die casting process molten metal, poured in the shot sleeve through a ladle. Movement of a plunger (piston) forces the metal inside the die in two stages. Firstly, the plunger moves initially with a low velocity at the first phase length. Secondly, velocity increases during the last phase of piston motion, and the injection pressure decreases when nearly all the liquid metal is injected into the die and solidifies. During this process, the flow of the metal inside the shot sleeve should be in laminar. Syrcos (2002) prevents turbulence, the parameters like plunger velocity, the first phase length, and injection pressure to be set accurately.

III. EXPERIMENTATION SETUP FOR THE ANALYSIS OF PROCESS PARAMETERS

The experiments and simulation of the rotor die casting component, were conducted on the high pressure die casting machine 100T, TCS model as shown in Figure 3 by varying above operating parameters as given in Table

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2, with 25 numbers of levels within the maximum and minimum range at four stages. The proposed experimentation set up for four parameters, as shown in Figure 4.

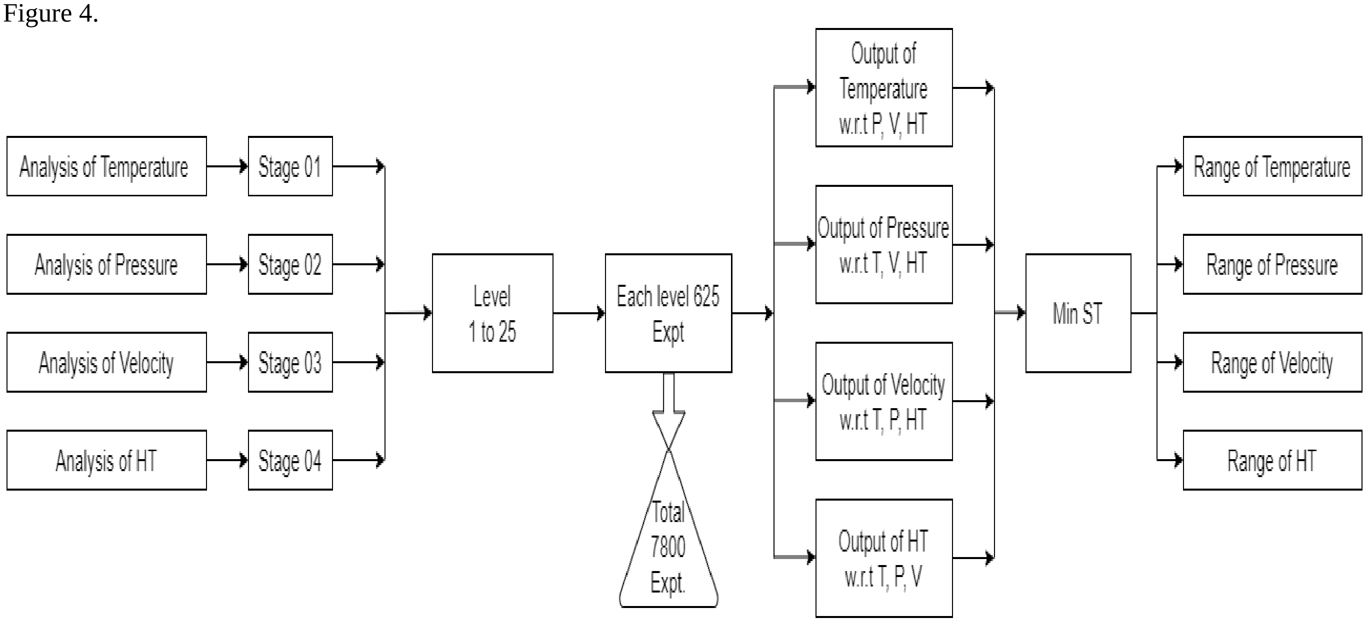

Figure 4: The proposed experimentation set up for solving flow for optimisation of parameters

Table 2: Process parameters with minimum to the maximum range with 25 experiments at each level

Level no.	Temperature (T) °C	Pressure (P) bar	Plunger Velocity(V) m/s	Holding Time (HT) s
1	680	300	116.6	52
2	683	302	116.8	53
3	686	304	117	54
4	689	306	117.2	55
5	692	308	117.4	56
6	695	310	117.6	57
7	698	312	117.8	58
8	701	314	118	59
9	704	316	118.2	60
10	707	318	118.4	61
11	710	320	118.6	62
12	713	322	118.8	63
13	716	324	119	64
14	719	326	119.2	65
15	722	328	119.4	66
16	725	330	119.6	67
17	728	332	119.8	68
18	731	334	120	69
19	734	336	120.2	70
20	737	338	120.4	71
21	740	340	120.6	72
22	743	342	120.8	73
23	746	344	121	74
24	749	346	121.2	75
25	752	348	121.4	76

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The numerical simulation approach for the optimisation of the process parameters in HPDC for aluminium alloy is to minimise the solidification time, as shown in Figure 5, which is the function of temperature (T), pressure (P), velocity (V) and holding time (HT) and subjected at four stages.

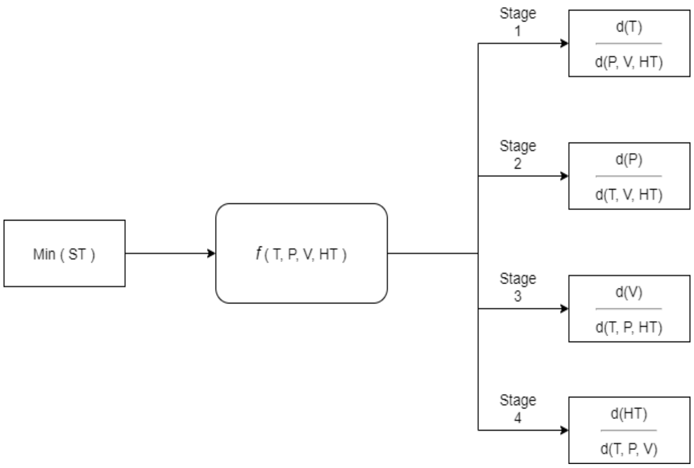

Figure 5: Block diagram showing four stages of numerical simulation for the optimisation of solidification time

Each of the four process parameters investigated in this paper is estimated at four stages. Each stage 25 levels with 625 experiments with three parameters varying from maximum to minimum range selected analysis to capture the influencing parameters for minimum solidification time.

To identify the minimum process parameters that affect the solidification time at each stage as shown in the block diagram, Figure 6, a minimum optimum finding program in visual, is used to determine the minimum optimal solution from each stage.

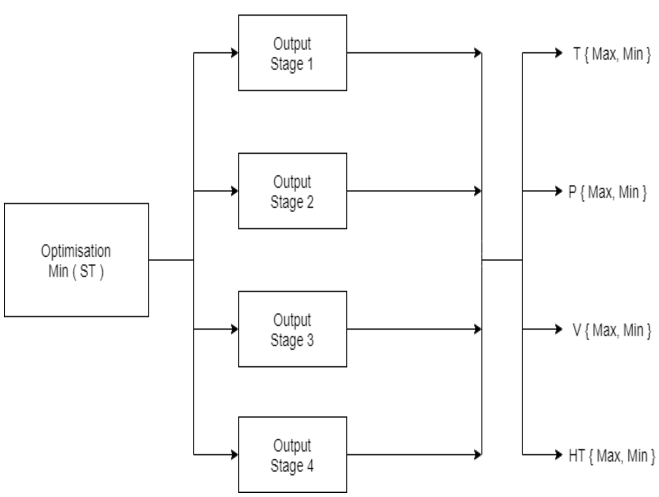

Figure 6: Flow diagram showing the final stage of a numerical simulation approach

IV. SIMULATION FOR ANALYSIS OF CASTING DEFECTS

For simulating actual casting with an outer radius of 100 mm, an inner radius of 25 mm, a height of 135 mm rotor component is analysed. The three-dimensional geometrical models of the castings, gating system, and mould, implemented using the Unigraphics NX4.0 software of UGS Corp, Ali [11]. The geometrical models are converted into *.x_t files to generate the finite element method (FEM) meshes by the MeshCAST module of ProCAST software, as shown in Figure 7. Once this module automatically generates the FEM meshes, the casting process parameters are regarded as initial boundary conditions for the simulation and defined in the pre-processor as reported in Fu and Wang (2014).

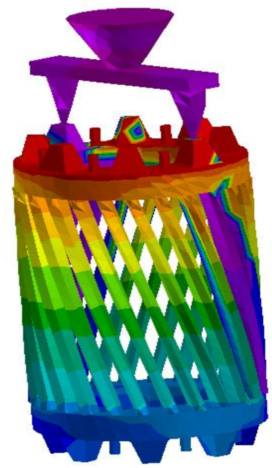

Figure 7: Meshed and position of cross-sections of the rotor component

The numerical simulation result for optimum defects by minimum solidification time is analysis. Once the calculation performed, the results viewed with the cast post-processor, called Visual-Viewer (Cast). As discussed in Fiorese, E. et al. (2016), various types of results are obtained from the software such as fraction solid, Shrinkage porosity, hotspots, the temperature at the filling time, and gas misruns sensitivity, and injection pressure.

V. SIMULATION OBSERVATIONS AND ANALYSIS

Simulation experiments performed at different combinations of process parameters suggested by a numerical approach for the high pressure die casting of a rotor component and process parameters impact minimising the solidifications time and the consistency

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of the experiments estimated using simulation techniques.

A) Temperature Analysis

Kumar, s. et al. (2012) found that molten metal temperature has an essential effect on defects. The difference in temperature affects the metal's fluidity; higher the temperature increases fluidity but can also establish a reaction between the material and the surrounding. For the temperature analysis, the pressure, velocity, and holding time kept constant at each level of an experiment, and the temperature was varied, ranging from 683 to 752 °C, solidification time concerning hot spots, observed to find out the optimal parameters for the component and a cross-section AA and BB. The main emphasis was to check the temperature distribution, the filling time, and the total shrinkage porosity. Table 3, shows an analysis of temperature at stage one of level 16, an experiment from 376 to 400 (13Nos) and experiment number 392 an optimum combination found by the program for minimum solidification with pressure (33Mpa), velocity(119.6 m/s) and holding time(67 s) for rotor component, cross-section(CS) AA and BB.

Table 3: Analysis of temperature versus solidification time of rotor component and at cross-sections AA and BB for stage one

P= 330 bar HT=67 sec V=119.6 m/s Level 16	Temp. (ºC)	Solidification time (Secs)		
Exp. No.		Rotor component	CS BB	CS AA
376	680	16.54	15.23	14.56
378	686	13.45	12.38	11.36
380	692	17.89	16.23	15.32
382	698	12.36	11.23	10.78
384	704	10.11	9.89	9.58
386	710	16.78	15.64	14.56
388	716	13.45	12.45	11.56
390	722	16.54	15.45	14.23
392	728	9.68	9.45	8.35
394	734	11.56	10.78	9.98
396	740	12.53	11.56	10.23
398	746	14.98	14.98	13.87
400	752	13.54	12.68	11.78

To study the solidification pattern, stage 1, and level 16, which is the optimal combination of parameters to be set for the defect-free product, considered for graphical analysis, as shown in Figure 8 for the rotor component and cross-section at AA and BB.

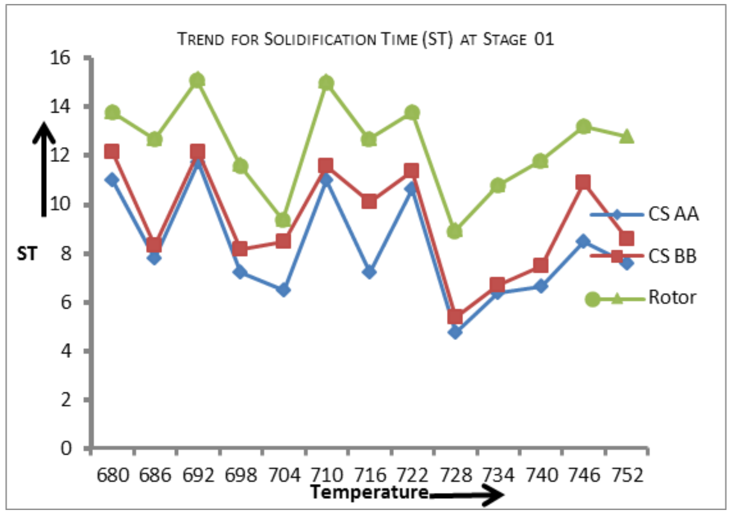
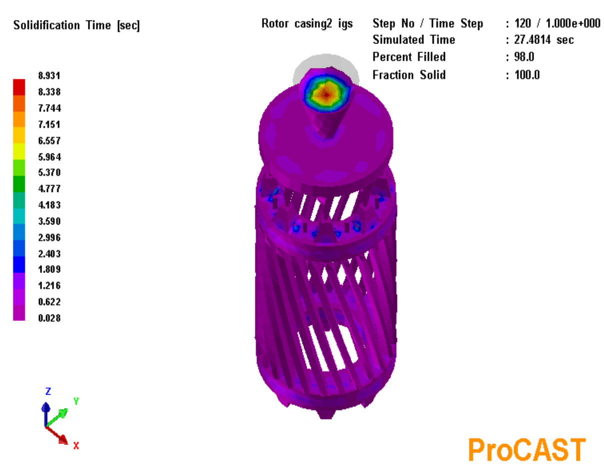


Figure 8: Graphical representation of temperature analysis of the rotor and at cross-sections AA and BB

As discussed in section III, output results through simulation by varying pressure, velocity, and holding time, as shown in Figure 9 (a, b, and C) for rotor component and cross-section at AA and BB, respectively.



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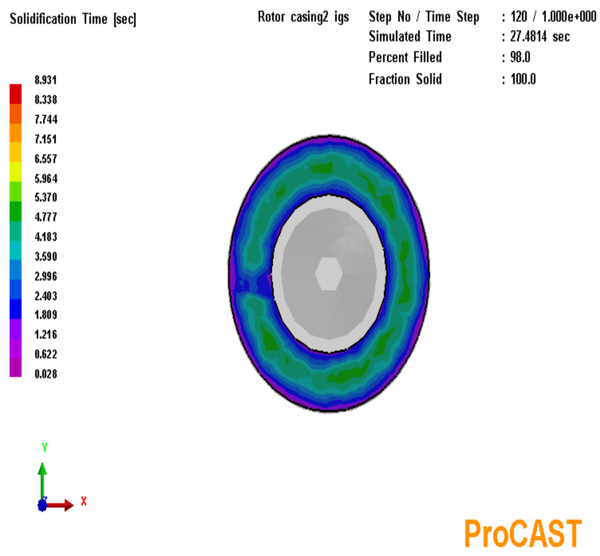

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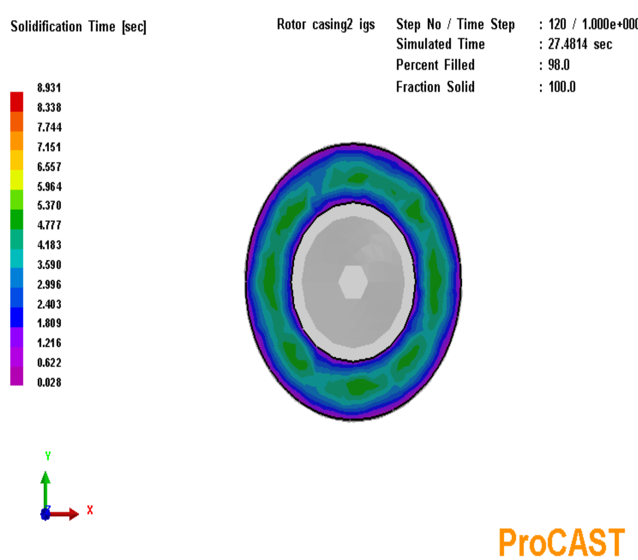

(c)

Figure 9: (a, b, and c) Simulation output for solidification time at rotor component, Cross-Section AA and BB.

Table 4 shows the results from the simulation analysis of stage 1, level 1 to 25, and experiment from 1 to 625 for rotor component, cross-section AA, and BB.

Table 4: Optimal parameters at stage 3 results for Minimum solidification time

Minimum Solidification Time					
	Pressure	Temp °C	Velocity m/s	Holding time (secs)	Min. Solidification Time (secs)
Rotor	330	728	119.6	67	8.93
CS AA					4.77
CS BB					5.37

B) Analysis of Pressure

As shown in Figure 6, in stage 2, numerical simulations for pressure analysis from 300 to 342 bar range by keeping temperature, velocity, and holding time constant at each level minimum solidification time for the rotor component cross-sections (CS) at AA and BB is performed. Table 5, shows an analysis of pressure at stage two of level 18, an experiment from 376 to 400 (13 Nos) and experiment number 441 an optimum combination found by the program for minimum solidification with temperature (731°C), velocity(120 m/s) and holding time(69 sec) for rotor component and cross-section AA and BB.

Table 5: Analysis of pressure versus solidification time of rotor component and at Cross-Sections AA and BB for stage two

T= 731 °C HT=69 secs V=120 m/s Level 18	Pressure (bar)	Solidification time (Sec)		
Exp. No.		Rotor Component	CS BB	CS AA
376	300	16.19	12.64	9.89
378	304	11.65	8.1	7.5
380	306	10.44	6.89	6.29
382	310	14.23	12.01	10.78
384	314	13.26	12.71	11.87

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386	318	14.96	12.41	11.81
388	322	12.78	11.23	10.63
390	326	14.4	13.45	10.56
392	330	8.91	5.36	4.76
394	334	10.65	7.1	6.5
396	338	14.36	12.81	11.56
398	342	14.54	13.56	10.23
400	346	12.39	10.45	9.87

To study the solidification pattern, stage 2, and level 18, which is the optimal combination of parameters to be set for the defect-free product, considered for graphical analysis, as shown in Figure 10 for the rotor component and cross-section at AA and BB.

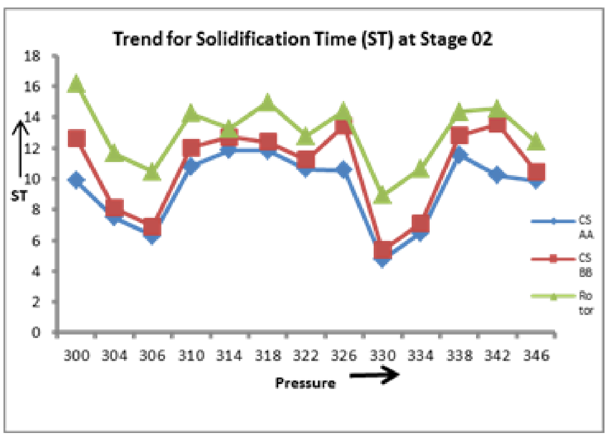
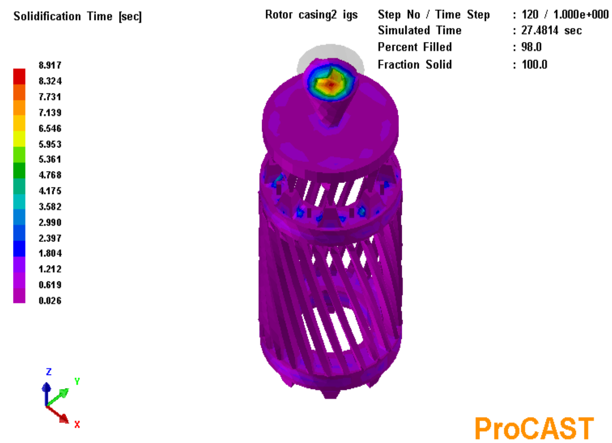


Figure 10: Graphical representation of pressure analysis at various sections

As discussed in section III, output results through simulation by varying temperature, velocity, and holding time, as shown in Figure 11 (a, b, and C) for rotor component and cross-section at AA and BB, respectively.



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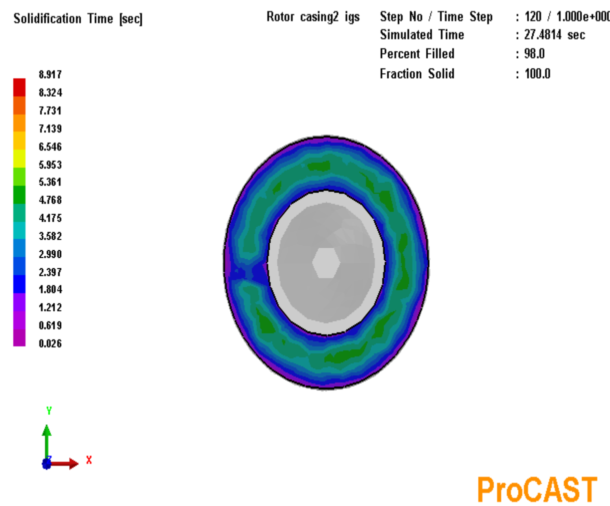

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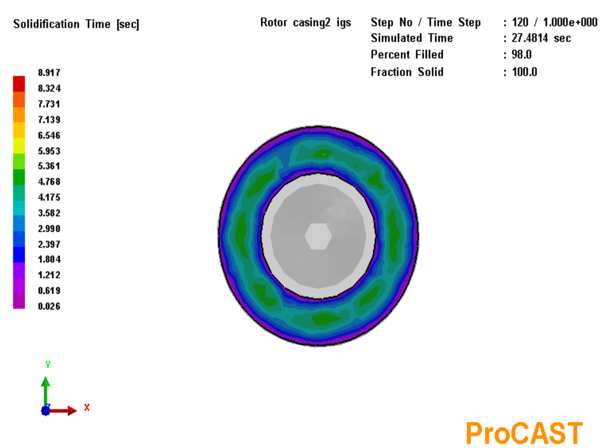

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Figure 11: (a, b, and c). Simulation output for solidification time at rotor component, Cross-Section AA, and BB.

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Table 6 shows the results from the simulation analysis of stage 2, level 1 to 25, and experiment from 1 to 625 for rotor component, cross-section AA, and BB.

Table 6: Optimal parameters at stage 2 results for minimum solidification time

Minimum Solidification Time					
	Pressure bar	Temp °C	Velocity m/sec	Holding time (secs)	Min. Solidification Time (secs)
Rotor	330	731	120	69	8.91
CS AA					4.76
CS BB					5.36

c) Analysis of Plunger Velocity

Figure 4 shows in stage three numerical simulation for plunger velocity analysis (116.6 to 121.4 m/s) by keeping temperature, pressure, and holding time constant at each level minimum solidification time for rotor component cross-sections(CS) at AA and BB is performed. Table 7, shows an analysis of plunger velocity at stage three of level 16, an experiment from 376 to 400 (13 Nos) and experiment number 392 an optimum combination found by the program for minimum solidification with temperature (725°C), pressure(330 bar) and holding time(67 sec) for rotor component and cross-section AA and BB.

Table 7: Analysis of plunger velocity versus solidification time of rotor component and at Cross-Sections AA and BB for stage three

T= 725 °C P=330 bar HT=119.8 secs Level 16	Velocity m/s	Solidification time (Sec)		
Exp. No.		Rotor Component	CS BB	CS AA
376	116.6	13.54	10.33	9.34
378	117	14.56	11.35	10.36
380	117.4	17.89	9.87	8.88
382	117.8	17.35	7.54	6.55
384	118.2	14.56	6.31	5.32
386	118.6	10.1	6.89	5.9
388	119	12.48	9.27	8.28
390	119.4	15.63	5.99	5.0
392	119.8	9.11	5.90	4.91
394	120.2	13.7	10.49	9.5
396	120.6	10.46	7.25	6.26
398	121	12.53	9.32	8.33
400	121.4	12.53	9.32	8.33

To study the solidification pattern, stage 3, and level 16, which is the optimal combination of parameters to be set for the defect-free product, considered for graphical analysis, as shown in Figure 12 for the rotor component and cross-section at AA and BB.

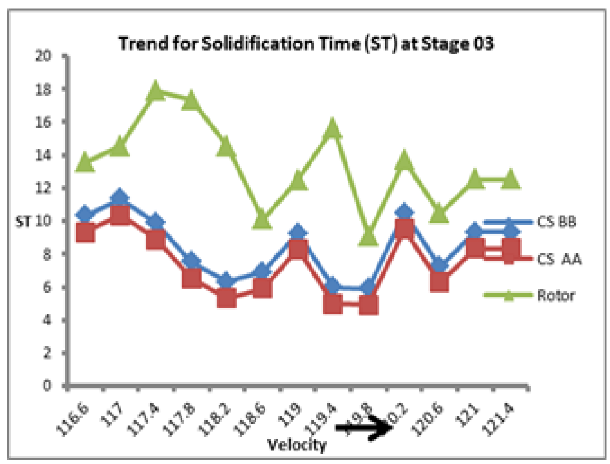

Figure 12: Graphical representation of plunger velocity analysis at various sections

As discussed in section III, output results through simulation by varying temperature, pressure, and holding time, as shown in Figure 13 (a, b and C) for rotor component and cross-section at AA and BB, respectively.

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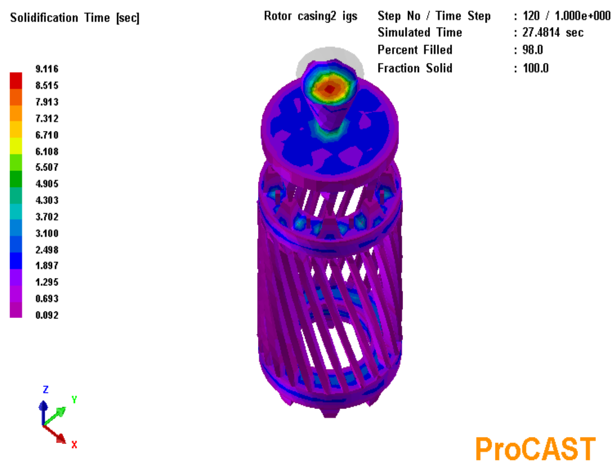

(a)

(b)

(c)

Figure 13: (a, b, and c) Simulation output for solidification time at rotor component, Cross-Section AA and BB.

Table 8 shows the results from the simulation analysis of stage 3, level 1 to 25, and experiment from 1 to 625 for rotor component, cross-section AA, and BB.

Table 8: Optimal parameters at stage 3 results for minimum solidification time

Minimum Solidification Time					
	Pressure bar	Temp °C	Velocity m/s	Holding time (sec)	Min. Solidification Time (sec)
Rotor	330	731	120	69	8.91
CS AA					4.76
CS BB					5.36

D) Analysis of Holding Time

In the current investigation, the effect of maximum applied pressure and molten temperature on the final components' solidification levels and at section AA and BB are of primary interest. Consequently, according to Wang, L. et al. (2011), holding time under intensified pressure influences the solidification time. As shown in Figure 6, in stage four, numerical simulation for holding time analysis (52 to 76 s) by keeping temperature, pressure, and velocity constant at each level minimum solidification time for rotor component and cross-sections(CS) at AA and BB is performed. Table 9, shows an analysis of holding time at stage four of level 17, an experiment from 401 to 425 (13 Nos) and experiment number 417 an optimum combination found by the program for minimum solidification with temperature (728°C), pressure(332 bar) and velocity(119.8 m/s) for rotor component and cross-section AA and BB.

Table 9: Analysis of holding time versus solidification time of rotor component and at Cross-Sections AA and BB for stage three

T= 728 °C P=332 bar HT=119.8 Level 17	Holding Time (sec)	Solidification time (Sec)		
Exp. No.		Rotor Component	CS BB	CS AA

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401	52	12.35	10.23	7.31
403	54	10.54	7.13	5.5
405	56	18.25	14.84	13.21
407	58	17.18	13.68	12.14
409	60	10.35	6.94	5.31
411	62	15.45	11.04	10.41
413	64	17.24	12.83	12.2
415	66	12.35	7.94	7.31
417	68	10.01	5.6	4.97
419	70	11.39	8.98	6.35
421	72	16.8	12.39	11.76
423	74	10.88	7.47	5.84
425	76	15.48	12.07	10.44

To study the solidification pattern, stage 4, and level 17, which is the optimal combination of parameters to be set for the defect-free product, considered for graphical analysis, as shown in Figure 14 for the rotor component and cross-section at AA and BB.

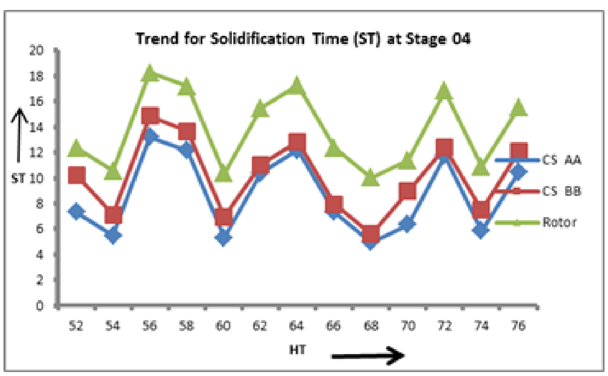
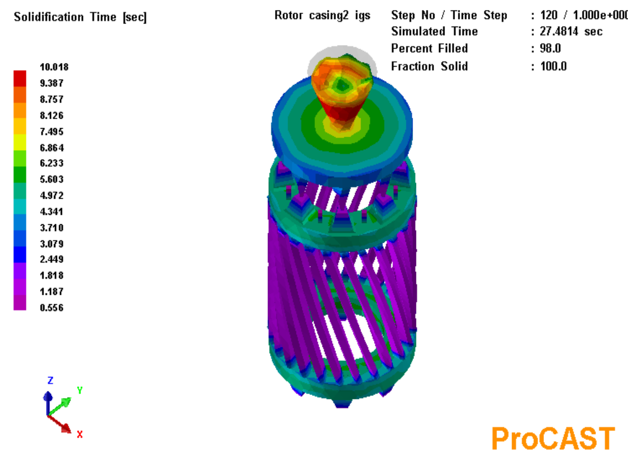


Figure 14: Graphical representation of holding time at various sections

As discussed in section III, output results through simulation by varying temperature, pressure, and holding time, as shown in Figure 15 (a, b and C) for rotor component and cross-section at AA and BB, respectively.



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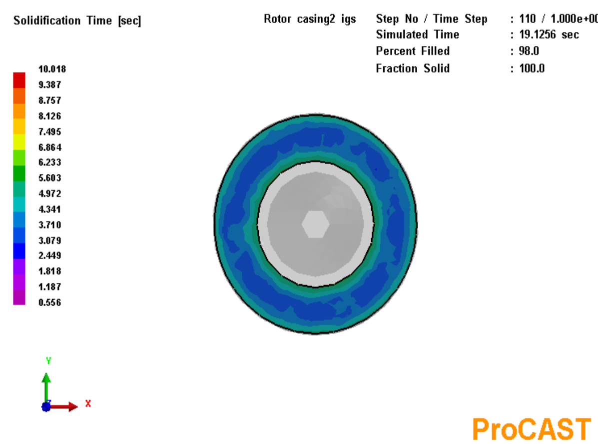

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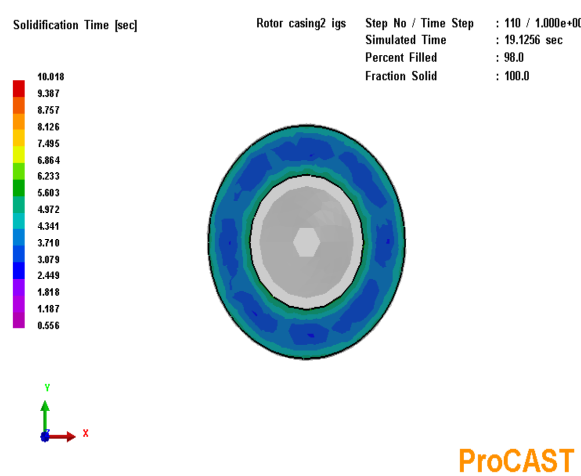

(c)

Figure 15: (a, b, and c) Simulation output for solidification time at rotor component, Cross-Section AA and BB.

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Table 10 shows the results from the simulation analysis of stage 4, level 1 to 25, and experiment from 1 to 625 for rotor component, cross-section AA, and BB.

Table 10: Optimal parameters at stage 4 results for minimum solidification time

Minimum Solidification Time					
	Pressure bar	Temp °C	Velocity m/s	Holding time (secs)	Min. Solidification Time (secs)
Rotor	332	728	119.8	68	10.01
CS AA					4.97
CS BB					5.60

IV. DISCUSSIONS AND CONCLUSIONS

As shown in Figure 4, the numerical simulation algorithm's flow optimises the process parameters to minimise the solidification time. 7800 simulation experiments have performed to study the effect of die casting process parameters on solidification time. Generally, when the solidification time is lower, internal defects such as blowholes and porosity is eliminated as per Zhang, X. et al. (2006). Therefore, the basic idea is to provide a decision tool for setting optimum parameters so that the component follows Six Sigma quality. A numerical simulation approach applied for optimising the die casting process parameters, and the results obtained using this method, as shown in Table 11, was useful in eliminating the defects in the die casting process.

Confirmation experiments with the optimal process parameters and the mean optimal settings are a pouring temperature of 730 _C, the pressure of 331 bar, plunger velocity 119.8 m/s, and holding time of 67 s are conducted due to the optimal process parameters, the testbed rejection of motors due to the rotor's contribution reduced from 4.35% to 0.89% (data from CGL). The dynamometer testing results also revealed that rotors produced under the optimum setting of process parameters have no significant defects. Similarly, the results obtained using simulation software ProCAST for filling time, total shrinkage porosity, and misrun sensitivity at optimised conditions show no presence of defects in casting, as shown in Figure 16 (a,b, and c).

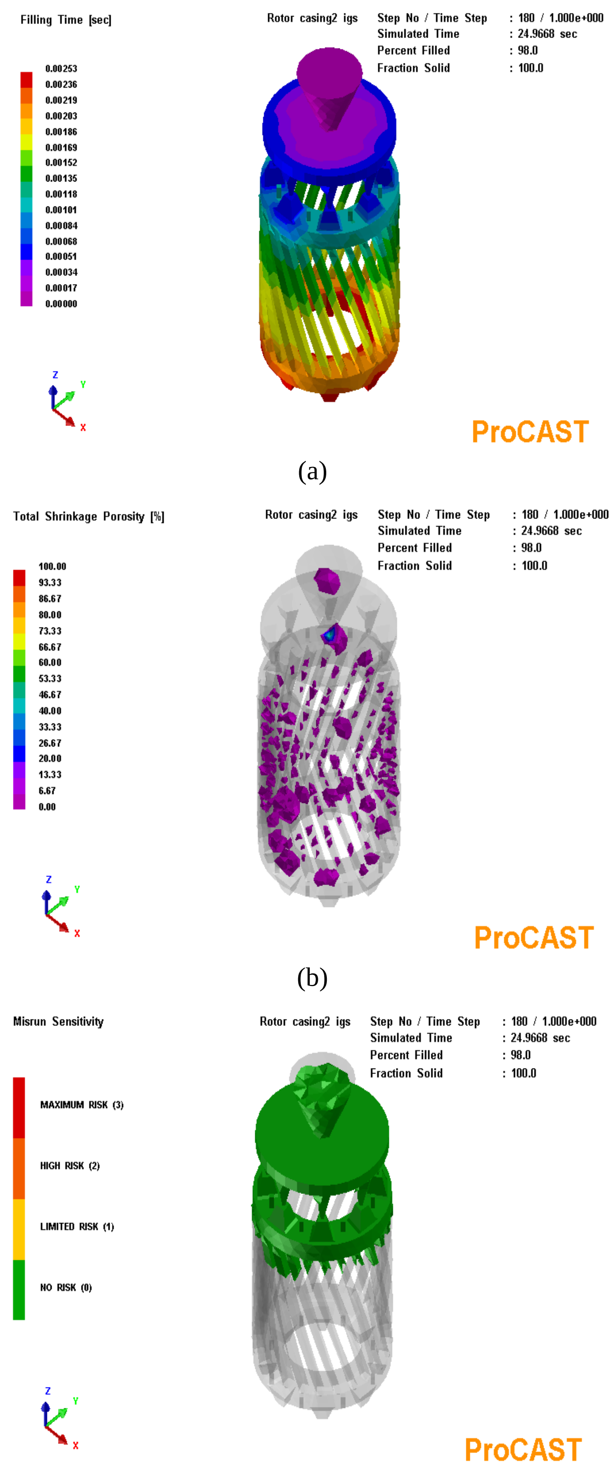

Figure 16: (a, b, c,) ProCAST simulated results for filling time, total shrinkage porosity and misrun sensitivity

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The contribution from the optimal parameters, the temperature, showed more influence on the casting quality than the other parameters, as observed from Figure 9, 11, 13, and 15. This paper's outcome was beneficial for finding the solution for casting defects due to incorrect setting of process parameters in die casting. Thus, a combination of numerical optimisation techniques and casting simulation serves as a tool to improve the casting product quality in die casting industries.

Table 11: Final two-sided optimisations die casting parameters

Temperature	Pressure	Velocity	Holding time	Min. Solidification Time
OUTPUT OF STAGE 1				
728	330	119.6	67	8.93
OUTPUT OF STAGE 2				
Temperature	Pressure	Velocity	Holding time	Min. Solidification Time
731	330	120	69	8.91
OUTPUT OF STAGE 3				
Temperature	Pressure	Velocity	Holding time	Min. Solidification Time
725	330	119.8	67	9.11
OUTPUT OF STAGE 4				
Temperature	Pressure	Velocity	Holding time	Min. Solidification Time
728	332	119.8	68	10.01

Two sided Optimum parameters:

i) Temperature(T) : $728 \leq T \leq 731$ T in ºC

ii) Pressure (p): $330 \leq P \leq 332$ P in bar

iii) Velocity (V): $119.6 \leq V \leq 120$ V in m/s

iv) Holding Time (HT): $65 \leq HT \leq 69$ HT in sec.

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