Jaya Algorithm for Optimization of Cooling Slope Casting Process Parameters

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Abstract. This study proposed the Jaya algorithm to estimate an improved value of billet performance through the cooling casting process. Jaya algorithm is a recent evolution-based algorithm that simulates using stochastic behaviour. The algorithm concept is the solution obtained for a given problem should move towards the best solution and should avoid the worst solution. This algorithm requires only the common control parameters and does not require any algorithm specific control parameters. To the best our knowledge, Jaya algorithm is not yet been used computational approach for optimization practice, particularly in the Cooling casting process. Three Cooling slope parameters process that influences the billet performance measurements, a maximum degree of sphericity and minimum grain size are pouring temperature, slanting angle, and travelling distance. The results show that the Jaya algorithm gave a better optimal solution for the maximum degree of sphericity and minimum particle size than experimental data.

1. Introduction

The cooling-slope (CS) casting process is one of the sixteen Semi-solid metal process (SSMP) techniques identified. It is a simple process that requires minimal equipment to produce billet for SSMP [1]. Practically, the CS process has several advantages, such as reduction of porosity and macro-segregation and better mechanical properties than those processed by conventional routes [2]. The degree of sphericity (DS) and particle size (PS) affects the strength of the billet performance and the billet's quality based on the previous literature. The DS and PS are commonly influenced by different cooling slope parameters process viz: pouring temperature, pouring distance, and slanting angle. These parameters are the major cooling slope process parameters used to affect billet performance and quality [3-4].

The CS process's success depends on selecting process parameters based on cost and quality factors. The major issue in CS process is how to obtain an accurate result of billet performance measurements such as DS and PS. Selection of optimal process parameters for PS and DS in the CS process remains one of the most challenging problems due to its complexity. Traditionally, the selection of optimal process parameters in the CS process is left to the foundry operator. However, this process mostly depends on foundry expertise. In such cases, foundry experience plays a major role, but sometimes it
isn't easy to maintain the accurate target for each experiment. Therefore, there is a need to develop a technique to solve this problem. The growth of advent technologies in the other manufacturing industry has introduced the computational approaches that have been considered widely by researchers to develop a model for giving an improved quality of a product.

Over the past two decades, many researchers have been attempt using a computational approach which is using population-based algorithms to optimize a wide range of manufacturing processes, such as Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Artificial Bee Colony (ABC), Differential Evolution (DE). The Jaya algorithm is recently a new population-based optimization algorithm proposed by R. Venkata Rao that reduces the computational burden concerning the initial values of algorithm parameters sensitive to optimal solutions. Note that the Jaya algorithm is simple to implement, does not require the turning off any specific algorithm parameters, and needs a few control parameters, i.e., the maximum number of generations, the number of design variables, and the size of the population. The Jaya algorithm works by finding a solution to the problem by moving to the best solution and avoiding the worst solution [5]. Jaya is a robust and simple optimization system implemented as a benchmarking tool for unconstraint and constraint problems [6].

This study considered the Jaya algorithm computational approach to optimize the CS process parameters: pouring temperature, pouring distance, and slanting angle to predict the maximum DS and minimum PS to produce the quality billet performance. The performance between the experimental data and the Jaya algorithm to optimize the operation reported. The findings are summarized, presented, and discussed.

2. Experimental
The cooling slope experimental process conducted by Gautham [7] referred to in this study. The process parameters performed by varying the pouring temperature, pouring distance, and slanting angle. ADC 12 aluminium alloy used as work material for experimentation. In a silicon carbide crucible, the alloy melted by the resistance furnace set at 750 °C. Then the molten alloy was cooled down to the three desired temperature (580°C, 585°C, and 590°C) poured onto an inclined plate. The molten alloy's temperature monitored with k-type thermocouples, located at three different slope lengths and a rapid data acquisition software, recorded their outputs. Water was circulated underneath the plate to cool it. The inclined plate's surfaces coated by a thin layer of boron nitride-coated layer to avoid sticking the molten alloy and facilitate a trouble-free melt flow. Then, pouring done at different cooling slope angles of 30°, 45°, and 60° with lengths of 400 mm, 500 mm, and 600 mm, respectively, to compare the inclined plate's effect with the same mould recorded.

2.1 Selection of process parameters
The proper selection of process parameters and their boundary range affected the accuracy of modelling and optimization of the cooling slope process. The process of the selection input variable, the limit of the boundary, and operating range based on the literature have done by Gautham [7] are presented in Table 1.

**Table 1.** The parameters and respond cooling slope casting process.

| Parameters          | Respond                  |
|---------------------|--------------------------|
| Pouring temperature | Pouring Distance Slanting angle |
| 580°C               | 400mm 30°                | Degree of |
| 585°C               | 500mm 45°                | Sphericity (DS) |
| 590°C               | 600mm 60°                | Particle size (PS) |

2.2. Design experiment and Regression model
Respond surface methodology (RSM), also known as central composite design (CCD), is used as the experimental design for the cooling slope casting process. Multiple regression models developed for both responses: GS and PS at 95% confidence level with pouring temperature, slanting angle, and slanting distance as input parameters. The models’ adequacy tested using the analysis of variance (ANOVA) and determination coefficients ($R^2$) values. The values of $R^2$ approaches indicate the models’ significant. Each model was then validated using mean square error (MSE), and root means square error (RMSE). Hence the CS model expressed as a polynomial model as Equation 1:

$$Y = \alpha + \beta_1 A + \beta_2 B + \beta_3 C + \beta_{12} AB + \beta_{13} AC + \beta_{23} BC + \beta_{11} A^2 + \beta_{22} B^2 + \beta_{33} C^2$$

where $\alpha$ is a constant, $\beta_i$ is the coefficient of linear term and $\beta_{ij}$ coefficient of the second-order model term. The input process parameter, which is slanting angle (A), pouring distance (B) and pouring temperature (C).

3. Optimization of Cooling-slope casting process

3.1. Application of Jaya algorithm in the cooling-slope casting process

The following steps describe the proposed method of applying the Jaya algorithm to solve the CS process:

Step 1 Define the input process parameters and objective functions. Input parameters: pouring temperature, pouring distance, and slanting angle. Objective functions: DS and PS.

Step 2 The mathematical models for DS and PS expressed as equation five and six, respectively as a function for Jaya algorithm. The process parameters bounds are expresses by Equation (4) until (6).

Maximize:

$$DS = -1503.37126 + 5.15697 A - 7.32285 B - 0.03 A^2 + 0.03 B^2 - 2.30390 C - 0.06 B^2 - 1.82529 E - 0.04 C^2$$

Minimize

$$PS = 2.22249 A + 0.005 - 759.44838 A - 1.07164 B - 1.74666 C + 1.45250 E - 0.03 A B - 0.64919 A^2 + 2.42483 E - 0.04 B^2 - 0.018044 C^2$$

580 $\leq$ A $\leq$ 590

400 $\leq$ B $\leq$ 600

30 $\leq$ C $\leq$ 60

Step 3 Identify the population size, number of variables, and stopping criteria.

Step 4 Generate and initialization of the positions.

Step 5 Identify the best and worst candidates among the population in terms of identified objective functions generated from equation and parameter boundaries from equation five till nine.

Step 6 Based on the best and worst solutions from step 5, substitute the value to modify all Candidate solutions using expressed as Equation 7:

$$X'_{i,j,k} = X_{i,j,k} + r_{1,i,j}[(X_{i,best,k}) - (|X_{i,j,k}|)] - r_{2,i,j}[(X_{i,worst,k}) - (|X_{i,j,k}|)]$$
where $X'_{i,j,k}$ is the modified value of the $i$-th design variable, $r_{1,i,j}$ and $r_{2,i,j}$ are randomly generated numbers within the range of (0–1) for the $j$-th control variable. $X_{i,\text{best},k}$ is the value of the $i$-th design variable for the top nominee solution. $X_{i,\text{worst},k}$ is the value of the $i$-th design variable for the inferior nominee solution. The second term of the above equation stands for the modified solution's propensity to proceed closer to the optimum solution. The third expression stands for the solution's tendency to eschew the worst solution.

Step 7 Solution candidates compared to check if the updated solution is better than the previous solution. The update candidate is accepted if the new candidate is better and rejected if the last solution is still better.

Step 8 The stopping criteria is applied in the algorithm; if the solutions satisfy the condition, the algorithm will stop, and otherwise, return to Step 4.

4. Results and Discussions

In this study, the mathematical regression model used for both responses in Jaya algorithm to optimize the CS process parameters. The model significance and coefficient determination values for all models presented in Table 2. From the summary ANOVA values analysis, both models were significant since their p-values were less than 0.05. A perfect fit model was observed and sustained by the coefficient of determination ($R^2$). All models obtained the coefficient values of more than 90%.

Furthermore, it indicated that all model explained more than 90% of the variance in the performance billet that can explain by cooling slope process parameters. Both models' accuracy validated between the actual data and the mathematical model. The values of mean square error and root mean square error calculated, as shown in Table 3. The smallest MSE and RMSE produced an accurate model between experimental and mathematical models. Table 3 shows that both models produce small MSE and RMSE, indicating that both models are significant for predicting and optimizing.

| Table 2. Summary of ANOVA value for P-values and $R^2$ |
|---------------------------------|--------------|--------|
| Type                           | P-values     | $R^2$  |
| Model RSM DS                   | 0.00         | 0.9927 |
| Model RSM PS                   | 0.00         | 0.9975 |

| Table 3. Mean square error (MSE) and root mean square error (RMSE) |
|--------------------|----------------|--------|
| Model               | MSE  | RMSE | MSE  | RMSE |
| RSM                 | 0.0001 | 1.797 | 0.001 | 1.340 |

Next, both models for DS and PS were used to investigate the Jaya optimization algorithm's capability in solving the optimization process problems. The DS and PS know that the algorithm has target capacities as a fitness function. Each billet performance's target capacities are the maximum degree of sphericity and minimum grain size. The algorithm's convergence rates to find the solution through 300 iterations illustrated in Figure 2 (a) and (b). The results show the Jaya algorithm convergence speed in less than 50th iteration for a maximum degree of sphericity values and minimum particle size, 34th and 27th, respectively to converge at the optimal solution.
Figure 2. Convergence curve for (a) degree of sphericity and (b) particle size.

In this study, the Jaya algorithm used the models and found the optimal values for all parameters and responses. The main objective to obtain the optimal processing parameters values to maximize the degree of sphericity and minimum particle grain size values through the cooling slope casting process. Tables 4 and 5 show the optimal values for each parameter and response obtained for both responses. Based on the result indicated in Table 4, the Jaya algorithm in this research is efficient. It is efficient to give better results, a maximum degree of sphericity value than other approaches in various Cooling-slope processes. The Jaya algorithm has also potentially solved different types of casting process performances. It gave a good solution for particle size, as indicated in Table 5, the minimum particle size value compares to other approaches.

Table 4. Optimum CS parameters and maximum degree of sphericity.

| Optimization       | Pouring Temperature | Pouring distance | Slanting angle | Degree of sphericity |
|--------------------|---------------------|------------------|----------------|----------------------|
| Experiment data [7]| 585                 | 500              | 45             | 0.866                |
| RSM [7]            | 585                 | 500              | 45             | 0.865                |
| Jaya algorithm     | 584.01              | 532.55           | 46.70          | 0.94                 |

Table 5. Optimum CS parameters and minimum particle size.

| Optimization       | Pouring Temperature | Pouring distance | Slanting angle | Particle Size |
|--------------------|---------------------|------------------|----------------|--------------|
| Experiment data [7]| 585                 | 500              | 45             | 49.3         |
| RSM [7]            | 585                 | 500              | 45             | 49.87        |
| Jaya algorithm     | 584.40              | 500              | 48.40          | 47.33        |

5. Conclusions

In this paper, the Jaya algorithm applied for both response models: the degree of sphericity and particle size. The significant model and coefficient determination values for both models obtained since the p-values were less than 0.05. All models showed coefficient values ($R^2$) of more than 90%. Furthermore, it indicated that the models explained more than 90% of the cooling slope casting process variability. Next, all the models’ accuracy was validated used MSE and RMSE. The results showed both models are significant since they produced small MSE and RMSE values. The Jaya algorithm is shown convergence speed is good, below 40 to converge at the optimal solution. Comparing process parameters and objective function values between the Jaya algorithm results and other experimental data also carried out. Proven that the Jaya algorithm gave a better optimal solution for a maximum degree of sphericity and minimum particle size than experimental data [7]. The Jaya algorithm in engineering and
optimization problems also recorded a good performance. Therefore, it can conclude that the Jaya algorithm is a good and simple algorithm to solve cooling-slope semi-solid casting process optimization problems. The optimal solution will provide flexibility to the process planner to choose the best parameter settings depending on the application.

References
[1] Mukkollu S R and Kumar A 2020 Mater. Today: Proc. 26 pp 1078–1081
[2] Dang B, Jian Z., Xu J 2018 Int. J. Mater. Res. 109(8) pp 729-734
[3] El-Kady E Y, El-Mahallawi I S, Mahmoud T S, Attia A, Mohammed S S, Monir A 2016 Mater. Sci. an Indian J. 14 279–287
[4] Van Thuong N, Zuhailawati H, Seman A A, Huy T D, Dhindaw B K 2015 J. Mater. Eng. Perform. 24 pp 2108–2116
[5] Rao R V 2019 Jaya: An Advanced Optimization Algorithm And Its Engineering: Springer Publication
[6] Rao R V, Rai D P, Ramkumar J, Balic J. 2016 Adv. Prod. Eng. Manag. 11(4) 271–286
[7] Gautam S K, Mandal N, Roy H, Lohar A K, Samanta S K, Sutradhar G 2018 J. Braz. Soc. Mech. Sci. 40(6) 1-15