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Synopsis Of

INVESTIGATIONS ON THE MATERIAL EFFICIENCY AND ECONOMICS OF THE HYBRID ADDITIVE MANUFACTURING PROCESS

A Thesis

To be submitted by

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Of

DOCTOR OF PHILOSOPHY

1 Introduction

Hybrid Additive Manufacturing (HAM) combines the capabilities of Additive Manufacturing (AM) and Subtractive Manufacturing (SM). This thesis focuses on HAM process involving blown powder Direct Energy Deposition (DED) as the AM process and CNC machining as the SM process. For certain applications, DED is still not preferred because of its long production time and relatively low accuracy compared with CNC milling. The limitation of CNC machining lies in machining complex shapes owing to tool inaccessibility, high temperatures, and faster tool wear while machining hard materials [1]. The purpose of developing these hybrid processes is to complement the abovementioned weaknesses of LMD and CNC milling. HAM is intended for manufacturing processes in which it cannot independently produce components and is also utilized for repairing parts [2].

In AM, hybridization with conventional processes is carried out to fulfil many objectives, in which (i) material efficiency with environmental and economic performance, (ii) cost of complexity, and (iii) quality involving dimensional/geometric tolerances and/or surface finish [3] are most important among all. This thesis focuses on the material efficiency in terms of environmental and economic performance.

2 Research Gap

Material cost is one of the major contributors in total cost especially when working with expensive materials, such as titanium and nickel alloys used in aerospace, automotive, and marine applications.

Viewing from the process optimisation point of view, by improving catchment efficiency considerable amount of material cost can be saved [4]. The catchment efficiency is defined as ratio of mass of the bead deposited on the substrate to the mass of the powder fed for deposition. The catchment efficiency is low when thin-wall parts (of thickness around 2 mm [5]) are built with low energy density. In addition, the fabrication of thin-walled parts in LMD is challenging because it is difficult to control the amount of material deposited in the narrow zone of the part [6]. Hence, it is of importance to monitor catchment efficiency, wetting angle and track dimensions such as track height and track width, for good dimensional accuracy.

As in the literature, it was reported that the responses - catchment efficiency, track height, track width, and wetting angle was found to 20% [7], 253 ± 4 μm [8], 1788 ± 6 μm [8], and 20 deg. ± 2 μm [8]. It can be improved by investigating the above-mentioned responses through process parameter studies.

In HAM, the part volume needs to decomposed for the AM and SM processes. From the process planning aspect, splitting the volume for the AM and SM processes in HAM is challenging, and it is important to develop volume partitioning strategies that could be both cost-effective and material efficient.

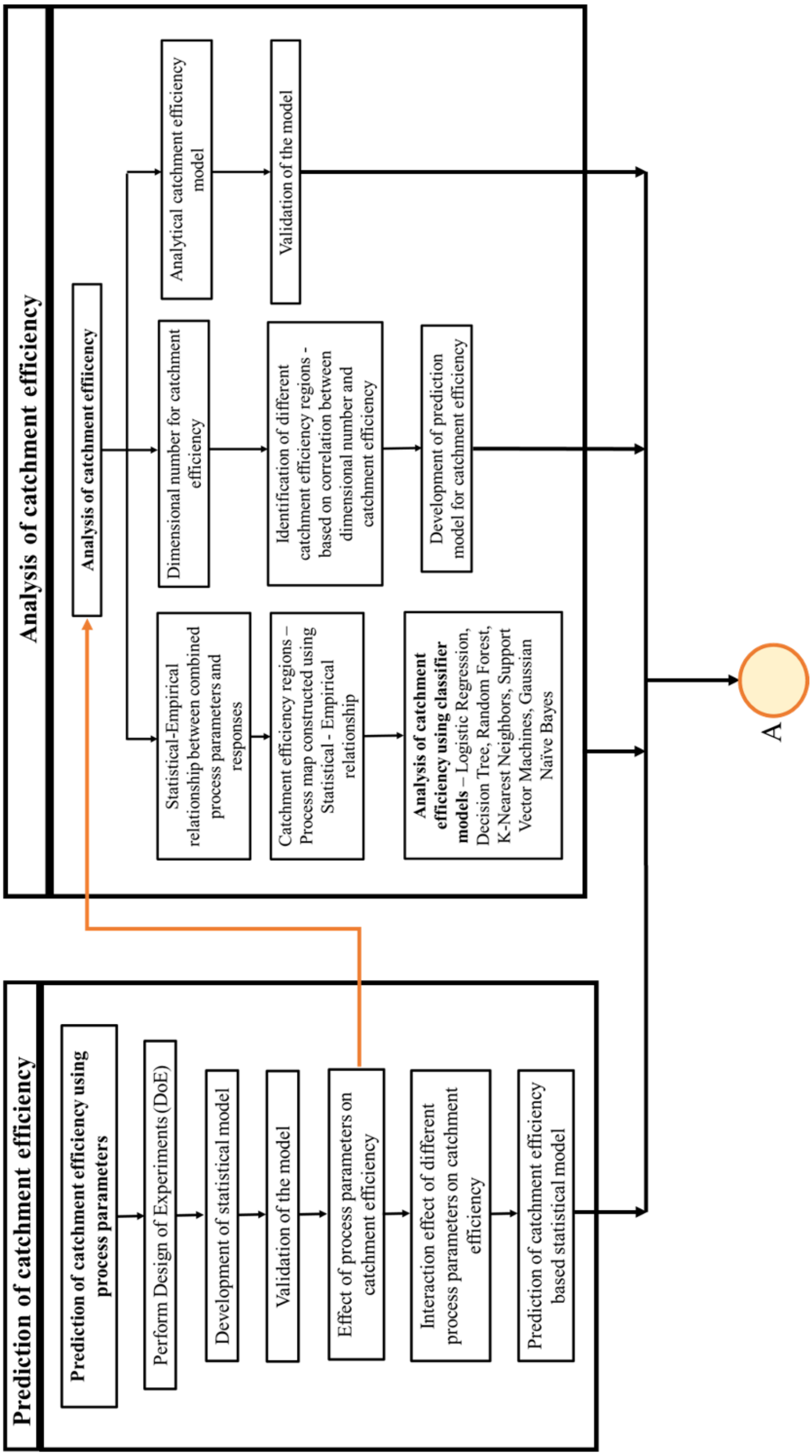
From the design optimisation aspect, Topology Optimisation with HAM constraint which involves both AM and SM constraint can be performed to reduce weight of the part thereby considerable amount of material saving can be achieved. The challenge lies in defining AM constraint for DED process and also manufacturing feasibility of the optimised thin wall part in HAM process.

3 Objectives

1. Study and investigate the parameters affecting catchment efficiency in blown powder DED process for building thin-walled parts and to develop an analytical model to predict catchment efficiency.
2. Develop an empirical-statistical method in order to establish the relationship between the chosen process parameters, catchment efficiency, and geometric characteristics.
3. Devise a dimensionless number to predict catchment efficiency based on combination of process parameters.
4. Propose cost effective and material efficient volume partitioning strategies for HAM process.

4 Overall Methodology

The work focusses on material efficiency in terms of economic performance. The material efficiency can be viewed at three different aspects – (i) Process optimization, (ii) Process planning and (iii) Design optimization as shown in Figure 1.



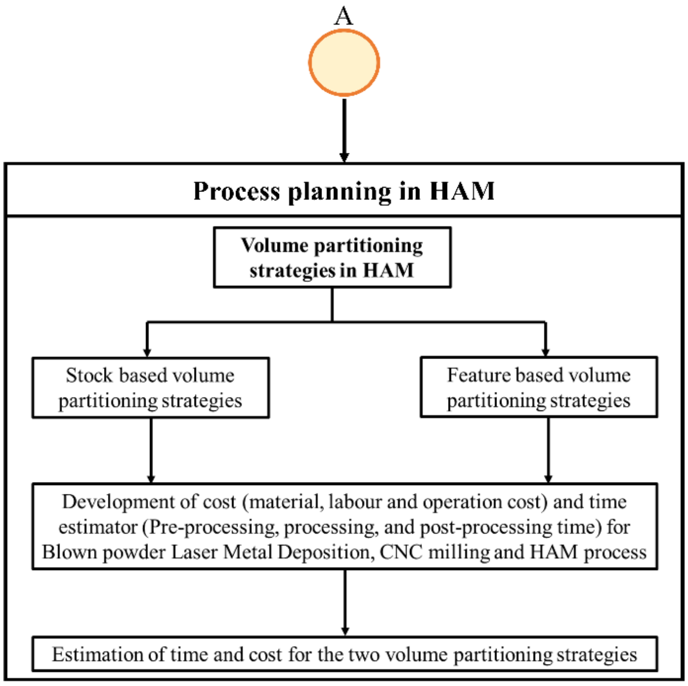


Fig. 1 Overview of the methodology

5. Results and discussion

5.1 Prediction of catchment efficiency based on regression models

In prediction of catchment efficiency, various process parameters affecting catchment efficiency were studied. Initially pilot tests were carried out to find the most influencing process parameters. The process parameter ranges were then identified and optimized using Design of Experiments (DoE) technique and the experimental set-up in which experiments were conducted is shown in Figure 2. A process map was modelled to identify optimal process parameter range (or) optimal operating zone to obtain maximum catchment efficiency.

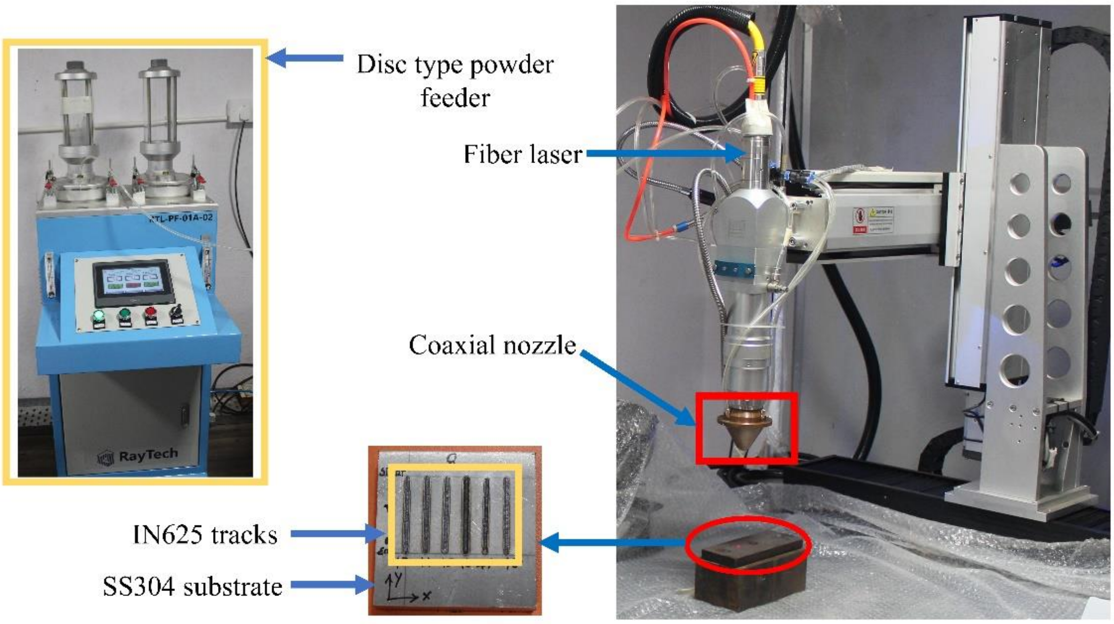


Fig. 2 Experimental set-up

5.1.1 Development of the statistical model

The correlation between process parameters such as laser power (P) in ‘W’, carrier gas flow rate ($\dot{m}_c$) in ‘l/hr’, deposition speed (v) in ‘mm/s’, stand-off distance (s) in ‘mm’, and powder feed rate (f_p) in ‘g/min’ and the responses – Catchment efficiency (η_c), track height, track (h) in ‘µm’, track width (w) in ‘µm’, and wetting angle (θ) in ‘deg.’. The interaction effect between P and s on η_c is shown in Figure 3 where different η_c regions can be seen.

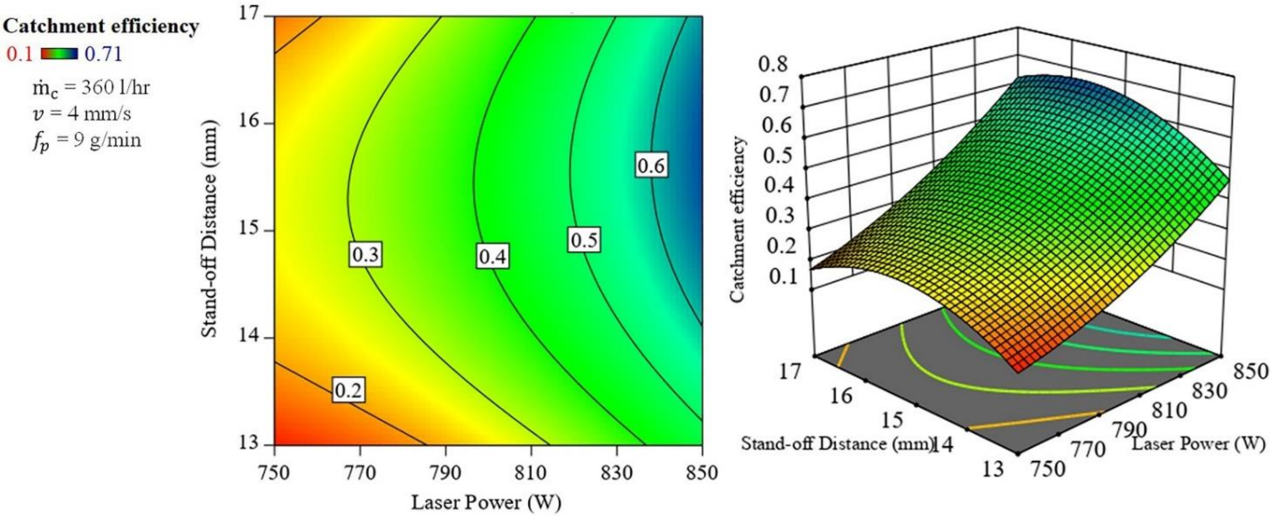
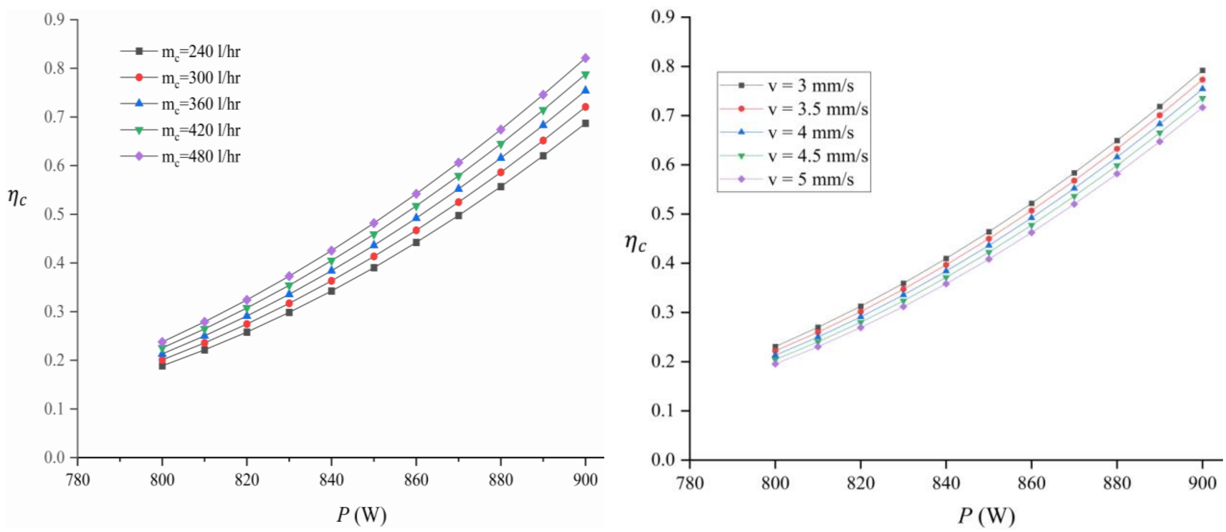


Fig. 3 Interaction effect of laser power and stand-off distance on catchment efficiency - (a) 3D surface graph and (b) contour graph

5.1.2 Development of analytical model for catchment efficiency

An analytical model was developed to predict η_c using the process parameters considered for the study. In this thesis, Goldak’s or double ellipsoidal power density distribution was considered based on which analytical model of η_c was derived for three jet coaxial nozzle. The effect of different process parameters on η_c is shown in the Figure 4 (a) and (b) respectively.



(a) (b)

Fig. 4 Effect of (a) $\dot{m}_c$ and (b) v in η_c

Table 1. Comparison of the analytical model, empirical model, and experimental catchment efficiency

P (W)	$\dot{m}_c$ (l/hr)	v (mm/s)	s (mm)	f_p (g/min)		η_c
850	360	4	15	9	Analytical model	0.67
					Experimental	0.71
					% Error	7.8

5.2 Analysis of catchment efficiency using dimensional analysis and machine learning classifier models

5.2.1 Statistical analysis

A process map constructed for identifying optimal process parameters to obtain a single continuous track with higher η_c is shown in Figure 5. The process map identifies four distinct zones: (i) Poor catchment efficiency zone is the region that indicates single tracks with poor material deposition and significantly less η_c. (ii) Low catchment efficiency zone is the region that indicates single tracks with discontinuous and inconsistent width. (iii) Medium catchment efficiency zone is the region that indicates single tracks which are continuous and smooth with moderate η_c ranging from 0.4 to 0.5. (iv) High catchment efficiency zone is the region that indicates single tracks which are continuous with higher η_c (i.e., above 0.5).

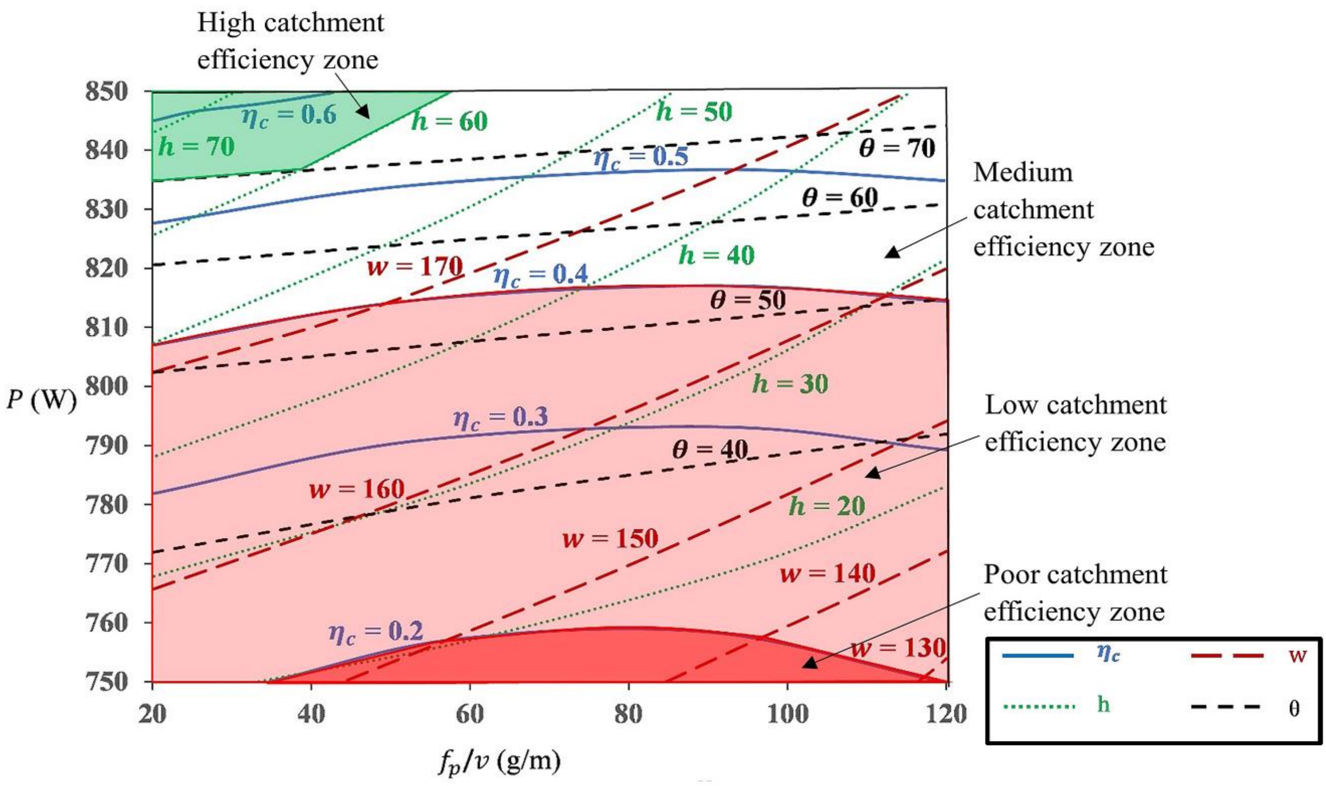


Fig. 5 Process map for deposition of IN625 powders on SS304 substrate - P vs. f_p/v

5.2.2 Formulation of dimensionless number to predict catchment efficiency

A dimensionless number was formulated to predict catchment efficiency using Buckingham -Π, a dimensional analysis method. Four different process parameters were chosen to formulate the dimensionless number to predict the catchment efficiency. The correlation between the normalized Π_1 and η_c was established with a R^2 value of 0.9 indicating a strong relationship, as shown in Figure 5. The three different η_c regions with actual and normalised Π_1 ranges are shown in Table 2.

Table 2. Three different η_c regions with actual and normalised Π_1 ranges.

Region	η_c **(%)**	**Normalised** Π_1
Low η_c	< 20	Below 0.11
Medium η_c	20 - 60	Between 0.11 – 0.69
High η_c	> 60	Above 0.69

From the correlation between Π_1 and Π_2, C and α was determined using regression. It was found that C = 1.0519 and α = 1.1009. η_c can be calculated using the equation (2) obtained by dimensional analysis.

$$\eta_c = l\ P^{1/4}\ f_p^{-1/4}\ \dot{m}_c^{-1/2}\ \mathrm{C}\ {\Pi_2}^{\alpha} \tag{2}$$

Three different experiments, as shown in Table 3, were performed to validate the predicted η_c. The R^2 value and the prediction error % was found to be 0.90 and 7.1% respectively. This is well within the agreeable percentage of error in prediction.

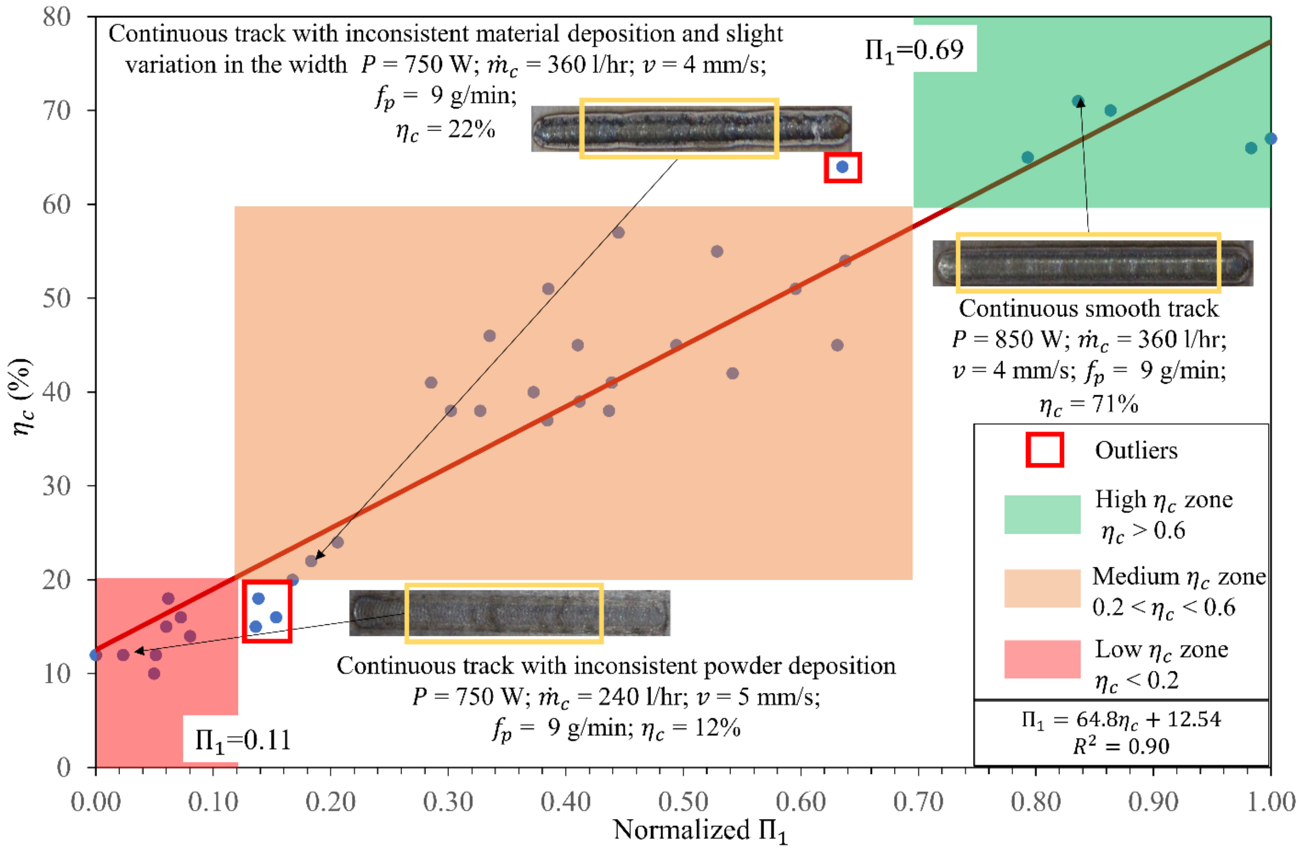


Fig. 5 Normalized Π_1 (vs) η_c

Table 3. Validation of the predicted η_c.

Exp. no	Region	P (W)	$\dot{m}_c$ (l/hr)	v (mm/s)	f_p (g/min)	Predicted η_c (%)	Experimental η_c (%)	% Error
1	Low η_c	775	300	3.5	7.5	26	28	5.92
2	Medium η_c	825	420	4.5	10.5	57	53	7.08
3	High η_c	850	360	4	9	67	71	6.41

5.2.3 Analysis of catchment efficiency using classifier models

Different classifier models – Logistic regression model, Decision tree, Random forest, Support Vector Machines, Gaussian Naive Bayes, and K-Nearest Neighbours were used to analysis the catchment efficiency. The comparison of prediction accuracy between the classifier models is shown in Figure 6.

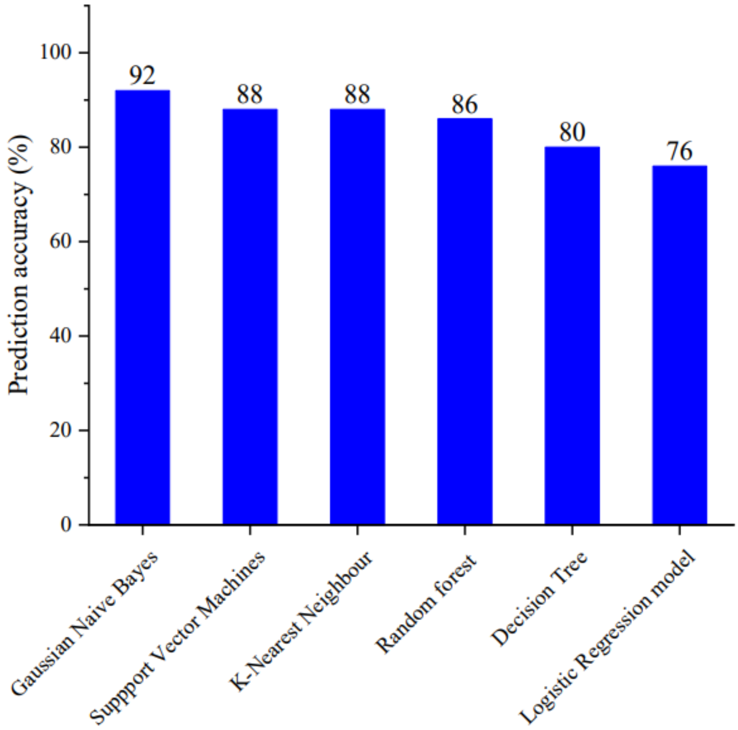


Fig. 6. Comparison of prediction accuracy between the classifier models

5.3 Analysis of process planning strategies on catchment efficiency and cost

In process planning in HAM, two different volume partition strategies - (i) Feature-based volume partitioning method (ii) Stock-based near net-shaping volume partitioning method was proposed. In feature-based volume partitioning method, the part volume is decomposed to AM and SM feature and in stock-based near net-shaping volume partitioning method, the entire part is built with some percentage of stock (W_s) in AM which is then post machined in SM.

5.3.1 Case studies

For partitioning geometry, we have selected two geometries – (i) Turbine blade (ii) Impeller as shown in Figure 7, where the partitioning can be exemplified because of the change in shape and size of the parts and also because of their free-form geometries.

In HAM – Stock based near net-shaping volume partitioning method; the entire part was built with W_s% stock which is then machined in SM as shown in Figure 8. In HAM – Feature based volume partitioning method, features were decomposed as AM and SM feature(s) as shown in Figure 7. Figure 8 shows a different cost (Material, labour, and operation cost) comparison between SM and HAM methods for the case study considered.

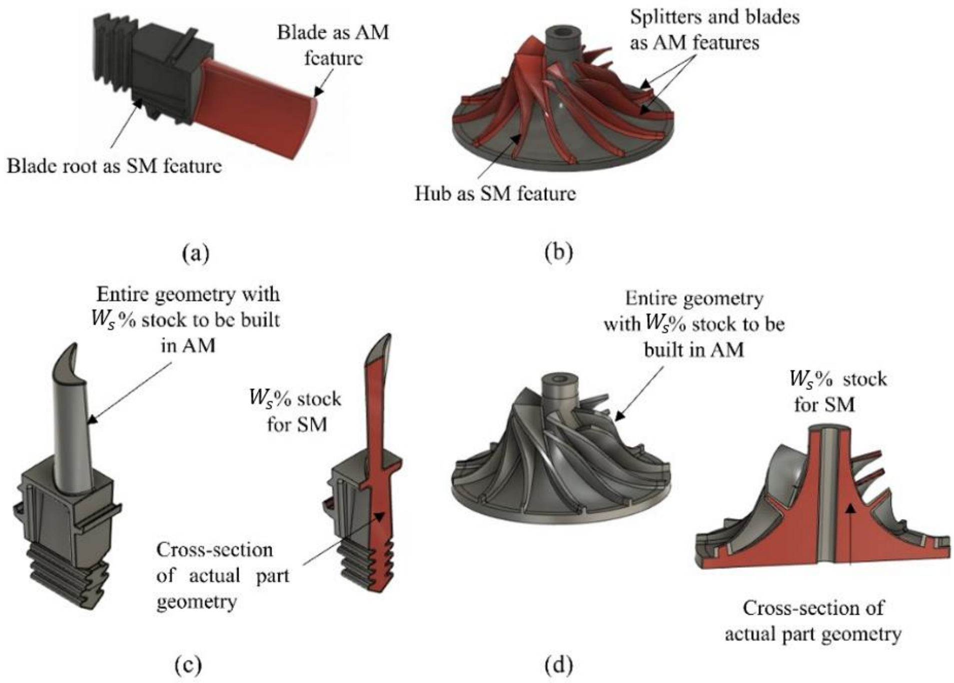


Fig. 7. Fabrication of Turbine Blade (a and c), and Impeller (b and d); by HAM –Feature based and Stock based volume partitioning method respectively

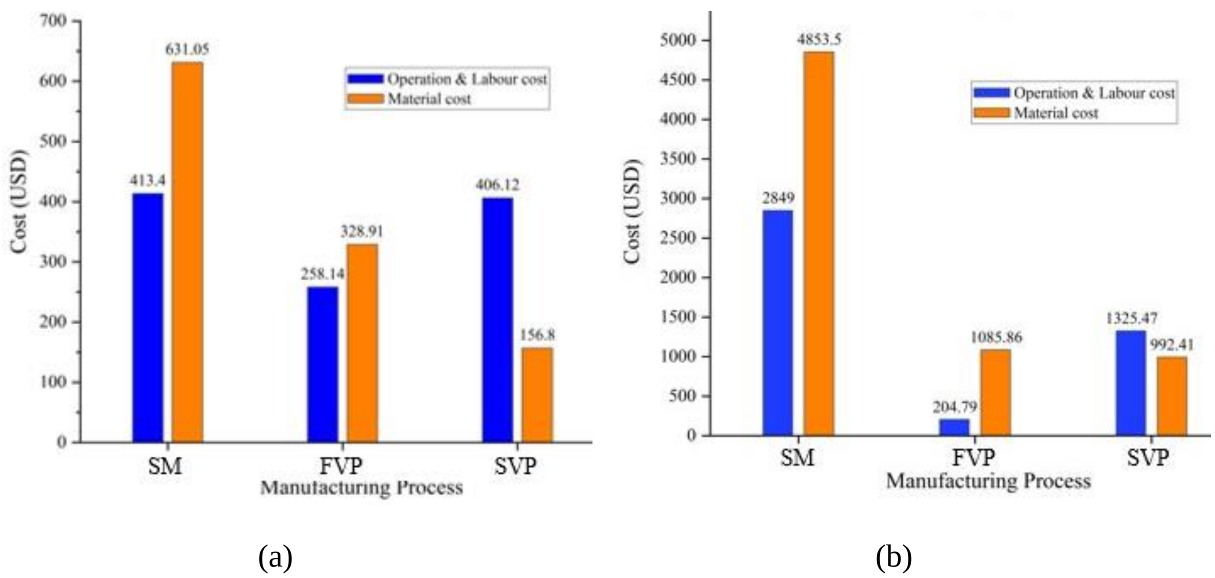


Fig. 8. Different cost comparison between SM and HAM methods - (a) Turbine blade, and (b) Impeller (HAM1 - Feature based volume partitioning method, HAM2 - Stock based near net-shaping volume partitioning method)

6 Conclusions and future scope

In the prediction of catchment efficiency, the process parameters influencing catchment efficiency were studied. Statistical, analytical, and empirical models were developed to predict catchment efficiency, which was then validated through experimentation. The prediction error of the proposed models was approximately 8%, which is within the limits of the scientific literature. In the analysis of catchment efficiency, a process map was constructed to identify different catchment efficiency zones – poor, low, medium, and high–which helped in choosing optimal process parameter ranges to achieve better bead quality with high catchment efficiency. In addition, a dimensionless number was devised to predict catchment efficiency. Based on dimensionless number ranges, different catchment efficiency regions (low, medium, and high) were identified. A model was developed using a dimensionless number to predict the catchment efficiency. The prediction error was found to be approximately 7%, which is within acceptable limits.

In the process planning method in HAM, two different volume partitioning strategies were proposed to decompose the volume of AM and SM in the HAM process. Two geometries - (i) Turbine blade, and (ii) Impeller, which of different sizes and shapes are considered as case studies to compare the proposed volume partition strategies with the SM process in terms of time, cost, material efficiency, and BFR. In the case study, the feature-based volume partitioning method was found to be material efficient, and the stock-based near-net shaping volume partitioning method was found to be cost-effective. Similarly, in the case study – Impeller, the feature-based volume partitioning method was found to be material efficient and cost effective than the stock based near net shaping volume partitioning method.

Nomenclature

a, b & $c_{f/r}$	- Semi-axes of the ellipsoid in 'mm'
C	- Proportionality constant
f_p	- Powder feed rate in 'g/min'
$f_{f/r}$	- Fractions of the heat deposited in the front and rear quadrant
h	- Track height in 'μm'
l	- Track length in 'mm'
$\dot{m}_c$	- Carrier gas flow rate in 'l/h'
P	- Laser power in 'W'
s	- Stand-off distance in 'mm'
v	- Deposition speed in 'mm/s'
w	- Track width in 'μm'

Greek letters

α	- Real number
η_c	- Catchment efficiency in '%'
θ	- Wetting angle in 'deg.'

Abbreviations

AM	- Additive Manufacturing
BFR	- Buy-to-Fly Ratio
CNC	- Computer Numerical Control
DED	- Direct Energy Deposition
DfAM	- Design for Additive Manufacturing
DoE	- Design of Experiments
HAM	- Hybrid Additive Manufacturing
SM	- Subtractive Manufacturing

7 Proposed thesis contents

1. Introduction

1.1 Additive manufacturing process
1.2 Application of AM in aerospace
1.3 Thin-wall fabrication of parts
1.4 Hybridization of AM processes
1.5 Classification of HAM process
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1.7 Catchment efficiency in DED process
1.8 Advantages of AM and HAM
1.9 Process planning challenges in HAM
1.10 Overall motivation

2. Literature survey

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2.2 Catchment efficiency,
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2.4 Geometric characteristics
2.5 Material efficiency and BFR
2.6 Cost models
2.7 Process planning in HAM
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2.9 Motivation from literature
2.10 Research gaps
2.11 Objectives
2.12 Organization of the thesis

3. Methodology

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3.2 Analysis of catchment efficiency
3.3 Process planning method and results

4. Prediction of catchment efficiency based on regression models

4.1 Design of experiments
4.2 Experimental setup
4.3 Results and discussion
4.4 Summary of the chapter

5. Analysis of catchment efficiency using dimensional analysis and ML classifier models

5.1 Dimensionless number for predicting catchment efficiency
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6. Analysis of process planning strategies on material efficiency and cost

6.1 Cost estimator for HAM
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6.4 Framework for TO with HAM constraints
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7. **Conclusions and Future scope**
   7.1 Summary and conclusions
   7.2 Conclusions
   7.3 Limitations
   7.4 Future scope

8 Research outcomes

Journal Publications

1. Reginald Elvis Peter and Senthilkumaran Kumaraguru. Influence of process parameters on the catchment efficiency in laser metal deposition tracks for building thin wall parts. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture (2022). **(IF: 2.6, Q1)**
2. Reginald Elvis Peter and Senthilkumaran Kumaraguru. Prediction of catchment efficiency in Direct Energy Deposition. (Manuscript under review)
3. Reginald Elvis Peter, Jayakrishnan Jayapal, Senthilkumaran Kumaraguru, and Manikandan. A Review of Methods and Tools for Lightweighting in Additive Manufacturing for Sustainable Production of Automotive Components. (Manuscript under review)

Conference Publications

1. Reginald Elvis PF, Kumaraguru S. Material Efficiency and Economics of Hybrid Additive Manufacturing. In International Manufacturing Science and Engineering Conference 2021 Jun 21 (Vol. 85062, p. V001T04A006). American Society of Mechanical Engineers.

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