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TAGUCHI-BASED OPTIMIZATION OF LAYER THICKNESS, DRYING TIME, AND BINDER SATURATION FOR IMPROVED MECHANICAL PROPERTIES IN BINDER JETTING ADDITIVE MANUFACTURING OF 17-4 PH STAINLESS STEEL

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ABSTRACT

This study employs the Taguchi method to optimize process parameters for enhancing mechanical properties in binder jetting additive manufacturing. Specifically, the orthogonal array and signal-to-noise ratio are utilized to investigate the effects of key process parameters on the additive manufacturing of 17-4 PH stainless steel. The study focuses on optimizing three critical parameters: layer thickness, drying time, and binder saturation, with a focus on their impact on mechanical properties. Experimental results demonstrate the efficacy of this optimization approach.

Keywords:
Optimization, Taguchi Method, signal-to-noise, Mechanical properties.

I. Introduction

In today's fast-paced industrial landscape, the primary objective is to produce high-quality products at low costs and with rapid turnaround times. To achieve this, modern manufacturing relies on Rapid prototyping machines. These additive manufacturing machines enable precise production with exceptionally high accuracy and significantly reduced processing times. The manufacturing landscape is evolving rapidly, driven by the need for complex, high-quality products at low costs and accelerated production times. Binder Jet Additive Manufacturing (BJAM) has emerged as a transformative technology, offering unparalleled flexibility and precision. This innovative process enables the selective binding of powdered materials, layer by layer, allowing manufacturers to create intricate geometries and functional parts with exceptional accuracy. By leveraging BJAM's capabilities, companies can significantly reduce production times and costs while maintaining superior product quality. As a result, BJAM is revolutionizing industries such as aerospace, automotive, and healthcare by enabling the rapid production of complex, customized parts. Mechaniacal properties is a measure of the technological quality of a product and a factor that greatly influences manufacturing cost. It describes the performance of the components in real time usage. The mechanism behind the formation of a better product is very complicated and process dependent. To select the process parameters properly, several mathematical models [1-5] have been constructed to establish the relationship between the process parameters and mechanical properties. Then, an objective function with constraints is formulated to solve the optimal process parameters using optimization techniques. Therefore, considerable knowledge and experience are required for this approach. In this study, an alternative approach based on the Taguchi method [6–8] is used to determine the desired cutting parameters more efficiency. There were two purposes of this research. The first was to demonstrate a systematic procedure of using Taguchi parameter design in process control of Binder Jet Additive Manufacturing machines. The second was to demonstrate a use of the Taguchi parameter design in order to identify the optimum Mechanical properties with a particular combination of process parameters in a Binder Jet Additive Manufacturing operation. The paper is organized in the following manner. An overview of the parameter design based on the Taguchi method is given first. Then, the parameter design with the multiple performance characteristics is introduced. The experimental detail of using the parameter design to determine and analyze the optimal Process parameters in Binder Jet Additive Manufacturing is described next. Finally, the paper concludes with a summary of this study.

II. Taguchi Methodology

Taguchi developed a methodology for applying designed experiments to improve product and process quality. His approach emphasizes the use of fewer experimental designs and provides a clearer understanding of variation and its economic consequences. Taguchi's philosophy is centered on the idea that engineering optimization should be carried out in a three-step approach: system design, parameter design, and tolerance design. System design involves creating a basic functional prototype, while parameter design aims to optimize process parameters to improve performance characteristics. Tolerance design involves determining the acceptable limits of variation for each parameter. Parameter design is a critical step in the Taguchi method. It involves optimizing process parameters to improve performance characteristics and reduce variation. The goal is to identify the optimal process parameter values that are insensitive to environmental conditions and noise factors.

Orthogonal Arrays and Signal-to-Noise Ratio

The Taguchi method uses orthogonal arrays to study the entire parameter space with a small number of experiments. A loss function is defined to calculate the deviation between the experimental value and the desired value. The loss function is then transformed into a signal-to-noise (S/N) ratio, which is used to measure the performance characteristic. There are three categories of performance characteristics: lower-the-better, higher-the-better, and nominal-the-better. The S/N ratio is calculated for each level of process parameters, and the larger S/N ratio corresponds to better performance. The S/N ratio formulas for the three categories of performance characteristics are:

Nominal-is-the-best: $S=NT = 10 \log (y^2 / s^2)$
Larger-is-the-better: $S=NL = -10 \log (1/n * \Sigma(1/y^2))$
Smaller-is-the-better: $S=NS = -10 \log (1/n * \Sigma y^2)$
where y is the observed data, s^2 is the variance, and n is the number of observations.

Taguchi Method in Binder Jet additive manufacturing

In this study, the Taguchi method is applied to optimize the process parameters Layer thickness, Drying time and Binder saturation in a Binder Jet additive manufacturing to achieve minimum porosity & maximum tensile strength, yield strength, elongation and hardness. The smaller-the-better quality characteristic is implemented, and the S/N ratio is calculated to determine the optimal process parameters.

The Taguchi method's parameter design approach for optimizing processes with multiple performance characteristics involves the following steps:

1. Identify the key performance characteristics and select the relevant process parameters for evaluation.
2. Determine the optimal number of levels for each process parameter and assess potential interactions between parameters.
3. Choose an appropriate orthogonal array and assign the process parameters to the array.
4. Execute the experiments according to the orthogonal array's configuration.
5. Calculating the total loss function and signal-to-noise (S/N) ratio to quantify the performance characteristics.
6. Analyzing the experimental results using the S/N ratio to identify optimal process parameters.
7. Selecting the optimal levels of process parameters based on the analysis.
8. Verifying the optimal process parameters through a confirmation experiment to validate the predicted improvements.

By following these steps, the Taguchi method enables efficient and effective optimization of complex processes with multiple performance characteristics.

2.1. Binder jet additive manufacturing process experiments

Binder jet additive manufacturing is a widely used 3D printing process in which a liquid binder is selectively deposited onto a bed of powder to create complex geometries. Three key process parameters, i.e., binder saturation, layer thickness, and drying time, must be optimized in a binder jet additive manufacturing operation. A common method of evaluating print quality in a binder jet additive manufacturing operation is based on the part's Porosity and mechanical properties. Porosity and mechanical properties are strongly correlated with process parameters such as binder saturation, layer thickness, and drying time. Proper selection of these process parameters can result in improved performance. Hence, optimization of the process parameters based on the parameter design of the Taguchi method is adopted to improve print quality in binder jet additive manufacturing.

2.2. Selection of process parameters and their levels

The binder jet additive manufacturing experiments were carried out on a Desktop Metal System using 17-4 PH steel powder. In the tests, the process parameters investigated were binder saturation, layer thickness, and drying time. Chemical composition of the 17-4 PH steel powder used in the experiments are shown in Table 1. The feasible range for the process parameters is binder saturation in the range 70-90%, layer thickness in the range 50-100 μm, and drying time in the range 20-30 seconds. Therefore, three levels of the process parameters were selected as shown in Table 2.

Table 1: Chemical Composition of 17-4PH Stainless steel powder

Element	C	Cr	Ni	Cu	Mn	Si	Nb+Ta	Fe
%Composition	0.07(max)	15.5-17.5	3-5	3-5	1.0(max)	1.0(max)	0.15-0.45	Balance

Table 2: Selected Process Parameters with ranges

S.NO	PARAMETER	LEVEL I	LEVEL II	LEVEL III
1	Layer Thickness	50	75	100
2	drying time	20	25	30
3	binder saturation	70	80	90

2.3. Determination of optimal process parameters

This section describes the application of an orthogonal array to minimize experiments and determine optimal process parameters. The results are analyzed using signal-to-noise (S/N) ratio technique. This helps to identify the optimal process parameters for improved porosity and mechanical properties, which are then verified. This approach efficiently optimizes process parameters, reducing experimentation time and improving performance. The results provide valuable insights for machining processes, enabling the achievement of desired results.

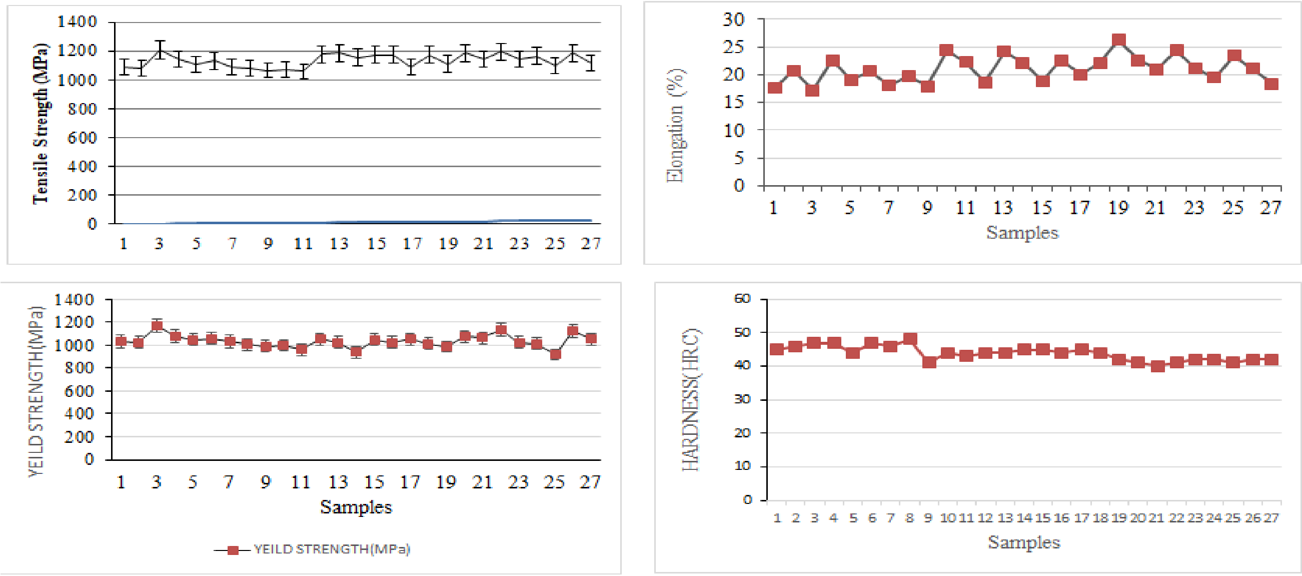
To apply the Taguchi method using Minitab, start by defining the problem and objective of the experiment, identifying the response variable(s) to be optimized. Next, select the process parameters (factors) that affect the response variable and determine the number of levels for each factor. Then, choose an orthogonal array (OA) that matches the number of factors and levels using Minitab's Create Taguchi Design function. Assign the process parameters to the columns of the OA and conduct the experiment according to the OA, collecting data for the response variable. Afterward, calculate the signal-to-noise (S/N) ratio for each experiment using Analyze Taguchi Design function. Analyze the results using Minitab's S/N ratio analysis tools to determine the optimal levels of the process parameters.

To determine the optimal process parameters, an L27 orthogonal array was employed. This array has 26 degrees of freedom, allowing it to accommodate three-level process parameters. The three cutting parameters were assigned to separate columns, resulting in 27 unique cutting parameter combinations. Consequently, only 27 experiments were necessary to investigate the entire parameter space using the L27 orthogonal array.

The experimental layout for the three process parameters using the L27 orthogonal array is presented in Table 3. The experimental results and signal-to-noise (S/N) ratio of porosity and mechanical properties are shown in Graph 1. This approach enables the efficient optimization of process parameters, minimizing experimentation time while improving quality.

Table 3: Experimental layout for the three process parameters

S.No	LAYER THICKNESS	DRYING TIME	BBINDER SATURATION	LAYER THICKNESS	DRYING TIME	BINDER SATURATION
1	1	1	1	50	20	70
2	1	1	2	50	20	80
3	1	1	3	50	20	90
4	1	2	1	50	25	70
5	1	2	2	50	25	80
6	1	2	3	50	25	90
7	1	3	1	50	30	70
8	1	3	2	50	30	80
9	2	3	3	50	30	90
10	2	1	1	75	20	70
11	2	1	2	75	20	80
12	2	1	3	75	20	90
13	2	2	1	75	25	70
14	2	2	2	75	25	80
15	2	2	3	75	25	90
16	2	3	1	75	30	70
17	2	3	2	75	30	80
18	2	3	3	75	30	90
19	3	1	1	100	20	70
20	3	1	2	100	20	80
21	3	1	3	100	20	90
22	3	2	1	100	25	70
23	3	2	2	100	25	80
24	3	2	3	100	25	90
25	3	3	1	100	30	70
26	3	3	2	100	30	80
27	3	3	3	100	30	90

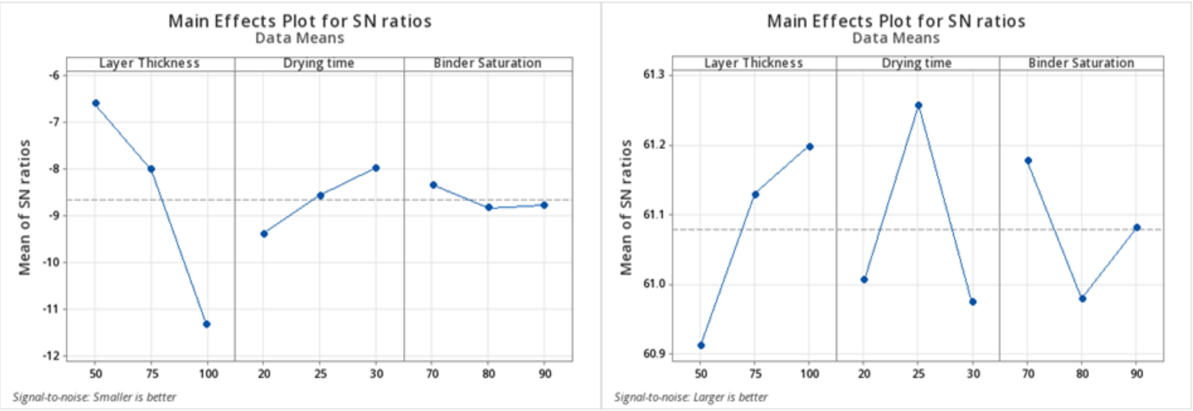


Graph 1: The experimental results of porosity and mechanical properties

III. Results and discussions

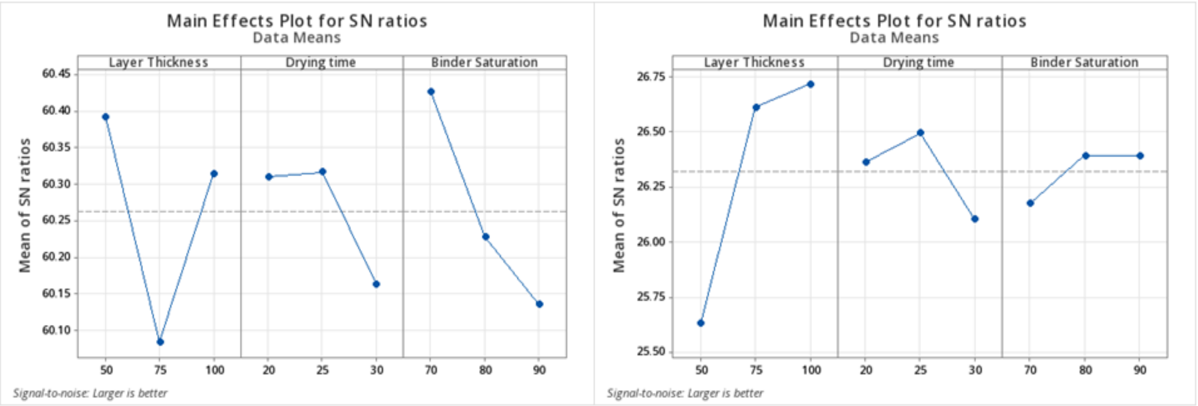
As previously mentioned, performance characteristics can be categorized into three types: lower-the-better, higher-the-better, and nominal-the-better. To achieve optimal machining performance, the lower-the-better characteristic is applied to porosity, while the higher-the-better characteristic is applied to tensile strength, yield strength, percentage of elongation, and hardness. The experimental results for these performance characteristics, along with their corresponding signal-to-noise (S/N) ratios calculated using Eq. (3), are presented in the table. Since the experimental design is orthogonal, the effects of each process parameter at different levels can be isolated. For instance, the mean S/N ratio for the insert radius at levels 1, 2, and 3 can be calculated by averaging the S/N ratios for experiments 1-3, 4-6, and 7-9, respectively. Similarly, the mean S/N ratio for each level of the other cutting parameters can be computed. The mean S/N ratio for each level of the process parameters is summarized in the mean S/N response table for porosity and mechanical properties. Additionally, the total mean S/N ratio for the 27 experiments is calculated. Figure 1 illustrates the mean S/N ratio graph for porosity and mechanical properties. The S/N ratio corresponds to the smaller variance of the output characteristics around the desired value. It is observed that most points are close to this line. Figure 2 shows the plot of predicted values versus residual values for the S/N ratio. The deviations are very small for each parameter and negligible.

Response Table for Signal to Noise Ratios



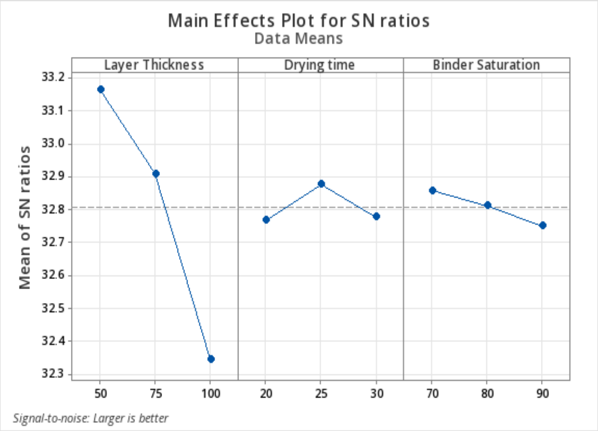
a) Response Table for Signal to Noise Ratios of porosity

b) Response Table for Signal to Noise Ratios of Tensile strength



c) Response Table for Signal to Noise Ratios of Yield Strength

d) Response Table for Signal to Noise Ratios of Percentage of elongation



e) Response Table for Signal to Noise Ratios of Hardness

The optimal combinations for various properties of 17-4 PH steel produced by binder jet additive manufacturing were determined using the Taguchi method and L27 orthogonal array. For porosity, the optimal combination was found to be A1B3C1, with a layer thickness of 50 mm, drying time of 30 sec, and binder saturation of 70%, resulting in a porosity of 2.01%, which matches the L27 orthogonal array of experiments. The signal-to-noise ratio main effects plot for porosity confirmed that the optimal combination is A3-B3-C1. Similarly, for tensile strength, the optimal combination was A3B2C1, with a layer thickness of 100 mm, drying time of 25 sec, and binder saturation of 70%, resulting in a tensile strength of 1195.13 MPa, which also matches the L27 orthogonal array of experiments. The signal-to-noise ratio main effects plot for tensile strength confirmed that the optimal combination is A3-B2-C1. For yield strength, the optimal combination was A1B2C1, with a layer thickness of 50 mm, drying time of 26 sec, and binder saturation of 70%, resulting in a yield strength of 1143.45 MPa, which matches the L27 orthogonal array of experiments. The signal-to-noise ratio main effects plot for yield strength confirmed that the optimal combination is A1-B2-C1. For elongation, two optimal combinations were found: A3B2C2 and A3B2C3, with layer thicknesses of 100 mm, drying time of 25 sec, and binder saturations of 80% and 90%, respectively, resulting in elongations of 21.16% and 19.8%, which match the L27 orthogonal array of experiments. Finally, for hardness, the optimal combination was A1B2C1, with a layer thickness of 50 mm, drying time of 25 sec, and binder saturation of 70%, resulting in a hardness of 47 HRC, which matches the L27 orthogonal array of experiments. The signal-to-noise ratio main effects plot for hardness confirmed that the optimal combination is A1-B2-C1.

IV. Conclusions:

The binder jet additive manufacturing process experiments revealed that optimizing process parameters such as binder saturation, layer thickness, and drying time is crucial for achieving desired properties in 17-4 PH steel parts.

- Using the Taguchi method and L27 orthogonal array, the optimal combinations for porosity, tensile strength, yield strength, elongation, and hardness were determined.
- The results showed that the optimal combinations are A1B3C1 for porosity, A3B2C1 for tensile strength, A1B2C1 for yield strength, A3B2C2 and A3B2C3 for elongation, and A1B2C1 for hardness. These optimal combinations resulted in improved properties, including a porosity of 2.01%, tensile strength of 1195.13 MPa, yield strength of 1143.45 MPa, elongation of 21.16% and 19.8%, and hardness of 47 HRC.
- The study demonstrates the effectiveness of the Taguchi method in optimizing binder jet additive manufacturing process parameters to achieve desired properties in 17-4 PH steel parts.

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