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Design and Analysis of a Response Surface Model to Realize the Mechanical Properties of Stainless Steel in Additive Manufacturing

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***Abstract*—Additive manufacturing which is known as 3D printing, has revolutionized the production of complex structures, particularly in the field of materials science. This study investigates the impact of various manufacturing and post-manufacturing parameters on the mechanical properties and weight of stainless-steel specimens produced using additive manufacturing technology. The study provides insights into the effect of inner cell dimension, wall thickness, inner cells orientation angle, 3D printing orientation, surface roughness, and heat treatment on tensile strength, yield strength, Young's modulus, strain, and weight. Also, it provides insights about the optimization of the factors to achieve the best mechanical properties with the least weight. The findings of this study contribute to the understanding of the additive manufacturing process and its optimization for stainless steel, paving the way for more efficient and cost-effective production in the future.**

Keywords*— *Stainless Steel, Response Surface Methodology, Additive Manufacturing, Design of Experiment

I. INTRODUCTION

The manufacturing landscape has been significantly transformed with the emergence of additive manufacturing, colloquially known as 3D printing. This innovative technology has unlocked new frontiers in the realm of materials science, enabling the fabrication of intricate structures with unprecedented precision and repeatability. Additive Manufacturing provides widespread applications across various industries, including aerospace, automotive, healthcare, and consumer goods. One of the key materials extensively utilized in AM processes is stainless steel, renowned for its superior mechanical properties, corrosion resistance, and versatility.

Stainless steel has been increasingly used in architectural and structural applications because of their superior corrosion resistance, ease of maintenance and pleasing appearance. The mechanical properties of stainless steel are quite different from those of carbon steel. For carbon and low-alloy steels, the proportional limit is assumed to be at least 70 % of the yield point, but for stainless steel the proportional limit ranges from approximately 36 % - 60 % of the yield strength. [15]

Several applications already exist worldwide for structural and non-structural components made of SSs, all these steels are alloys of iron, chromium, nickel and to varying degrees' molybdenum. The characteristic corrosion resistance of stainless steel is dependent on the chromium content and is enhanced by additions of molybdenum and nitrogen. Nickel is added, primarily, to ensure the mechanical properties and the correct microstructure of the steel. Other alloying elements may be added to improve particular aspects of the stainless steel such as high temperature properties, enhanced strength or to facilitate particular processing routes [1].

In stainless steel additive manufacturing, optimizing process parameters to achieve desired material properties and printing quality is vital. Response Surface Methodology (RSM) is a powerful tool in this endeavor, offering a systematic approach to experiment design, process optimization, and performance prediction.

RSM enables researchers and engineers to explore the complex interplay between multiple process variables and the desired outcomes. By statistically modeling these relationships and conducting systematic experiments, RSM facilitates the identification of optimal process settings that maximize material performance while minimizing production costs and time. [14]

Several studies have successfully applied RSM in the field of materials science. For instance, [10] the researcher used RSM to optimize the heat treatment process of stainless steel, resulting in improved hardness and tensile strength. Similarly, [11] employed RSM to study the effect of welding parameters on the mechanical properties of stainless steel.

This research enlightens the exploration of additive manufacturing, with a specific focus on the production of stainless-steel specimens. The core of the research is to understanding the influence of several adjustable manufacturing and post-manufacturing parameters on the

mechanical attributes and weight of the additive manufactured products to optimize the production by employing a well-recognized scientific methodology which is Response Surface Methodology.
The research pivots around several key parameters, including the inner cell dimension, wall thickness, inner cell orientation angle, surface roughness, and heat treatment. These parameters play a pivotal role in the manufacturing process and are anticipated to significantly impact the final product's properties. The responses of the experiment, which serve as the dependent variables in this study, encompass tensile strength, yield strength, Young's modulus, strain, and weight. These responses provide a comprehensive understanding of the mechanical behavior of the specimens under different conditions. The goal of the experiment is to reduce cost and weight of the manufactured objects by partially evacuating the inner structure via an inner net of structured cells.
Adopting a well-recognized scientific methodology such as response surface methodology which lies under the big umbrella of statistical design of experiment is a strong approach to study and optimize an industrial problem or process. This study will enlighten some areas for other researchers to examine and study furthermore parameters and factors that affect the manufacturing processes in the field of additive manufacturing specially 316L stainless steel manufacturing.
Targeting a metal additive manufacturing technology to apply an experiment on could be challenging because it's a modern technology in comparison to conventional machining, it's hard to obtain and operate because of its limited manufacturers and innovators worldwide and the rareness of powder raw material suppliers. Previous challenges should be taking into consideration before adopting such technologies. In addition, the journey of this research faced many obstacles during design in understanding the ability and adjustable parameters of the machine that produces the product and communication with the manufacturers of the machine to ensure eliminate any factor that may harm the manufacturing process. Also the machines availability and dedication to the research was a challenge since the study were conducted in a manufacturing environment not in a research institute.

II. LITERATURE REVIEW

The mechanical properties of stainless steel, such as tensile and yield strength, Young's modulus, and strain are critical for many applications. These properties can be influenced by various factors, including manufacturing parameters and post-manufacturing treatments. Therefore, a comprehensive understanding of properties and factors affecting them is essential.
The stress-strain behavior of duplex and austenitic steels in a tensile test differs from that of carbon steels. Stainless steels are also characterized by:

- A high degree of plasticity between the proof stress and the ultimate tensile stress.
- Very good low-temperature toughness.
- A degree of anisotropy

The advent of additive manufacturing, colloquially known as 3D printing, has ushered in a new era in the field of materials science. This innovative technology has revolutionized the production of complex structures and made a significant stride in the field of materials science, enabling the creation of intricate designs with a high degree of precision and repeatability.
Additive Manufacturing (AM) provides the capability to relax the design and manufacturing constraints by creating products with advanced geometrical complexity and without the need for extensive machining. [2-3].
The AM technique allows for the creation of three-dimensional shape structures through a layer-by-layer process [4]. Three-dimensional computer-aided design (CAD) programs are used to design components with complex shapes that could not be manufactured via conventional processes such as casting or forging [5]. Among the AM techniques, selective laser melting (SLM) is the most versatile, allowing for the creation of functional parts with mechanical properties similar to those of conventionally produced materials [6]. The wide variety of materials that can be produced, together with the low surface roughness achieved, are what differentiates this technique from other production methods [7]. The building process is achieved by the successive consolidation of molten powder layers. A high-temperature laser beam melts the powder of the first layer (from 0.02 mm to 0.1 mm) [1]. The second layer of metal powder is spread out over the surface, and the same operation is repeated until the building process is completed. However, this technique still presents some challenges that must be addressed in order to improve the performance of the manufactured parts [8].
Response Surface Methodology is a collection of statistical and mathematical techniques useful for developing, improving, and optimizing processes. It is a method used to model and analyze problems in which a response of interest is influenced by several variables and the objective is to optimize this response. The heart of RSM lies in the development of mathematical models that reflect the relationship between the factors and the responses. They are the keys to unlocking the optimal levels of the factors that maximize or minimize the responses [12].
To elaborate more about the impact and benefits of adopting RSM methodology in industrial applications some studies used RSM as a very beneficial tool. According to the researcher by applying Response Surface Methodology (RSM) the experiment had a structured framework for efficiently traversing the multidimensional parameter space, by this means augmenting the comprehension of the process dynamics and facilitating its optimization. On the other hand, leveraging predictive models derived from RSM successfully identified the optimal combination of culture conditions, yielding significant enhancements in both product yield and purity. A significant advantage is the graphical representations afforded by RSM, including contour plots and response surface plots, served as invaluable tools for visually interpreting the relationships between process variables and response variables, thereby aiding in informed decision-making and process optimization. By systematically varying culture parameters within the experimental domain defined by RSM allowed the researcher to uncover optimal operating conditions, maximizing desired biotransformation while minimizing undesirable by-products. [13]

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According to the researcher by utilizing Response Surface Methodology, the study analytically optimized and enhanced the efficiency of the process. It functioned as the most valuable tool in the analysis, enabling to model the complex relationships between different factors and the quality of phenolic-rich cinnamon extracts. The study utilized Response Surface Methodology to methodically investigate how varying extraction parameters impacted both the quantity and biological activity of phenolic extracts from cinnamon, offering significant insights beneficial to the food industry. Also, RSM fine-tuned the ultrasound-assisted extraction technique to obtain high-quality cinnamon extracts rich in phenolic compounds, underscoring the effectiveness and efficiency of this sophisticated extraction method. The application of Response Surface Methodology steered the exploration into extracting phenolic compounds from cinnamon, providing a structured approach to designing experiments and refining processes, thus furnishing invaluable information crucial for the advancement of functional food and health product development. [14]

III. METHOD AND METHODOLOGY

The experiment consists of five main phases starts with design, manufacturing and post-manufacturing activities, mechanical testing, data collection and data analysis.

3.1 Defining the factors and responses of the experiment

Factors that affect the manufacturing process and final product along with their types and levels as shown on Table 1 after realizing the machine's capabilities.

Table 1: factors that have been obtained from the machine's capabilities.

No.	Factor	Type	Level		
1	Inner Cell Dimension	Numerical	0.25 – 1 mm		
2	Wall thickness	Numerical	2 – 4 mm		
3	Inner Cells Orientation Angle	Numerical	0° – 45°		
4	3D Printing Orientation	Categorical	Vertical	Horizontal	Diagonal
5	Surface Roughness	Categorical	No	Sand blasting	Machining
6	Heat Treatment	Categorical	No	Annealing	Stress Relief

Responses that will be obtained and recorded after performing a destructive test (tensile test) on the specimens of the experiment are as follow: Tensile Strength (MPa), Yield Strength (MPa), Young's Modulus (GPa), and Strain (%). While the only response to obtain prior to the destructive test is the weight (g).

The experimental design table is generated through design expert software based on the factors of the study, their types and levels as a response Surface design of experiment as shown table 2:

Table 2: Experimental design table

Runs	FACTORS					
	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6
	A: Inner Cell Dimension	B: Wall thickness	C: Inner Cells Orientation Angle	D:3D Printing Orientation	E: Surface Roughness	F: Heat Treatment
1	1.00	2.00	45.0	Horizontal	Machining	Stress Relief
2	0.25	2.00	45.0	Diagonal	No	Annealing
3	0.58	2.00	45.0	Horizontal	No	Annealing
4	1.00	2.00	45.0	Vertical	No	Annealing
5	0.58	2.00	45.0	Vertical	No	Stress Relief
6	1.00	4.00	44.0	Diagonal	Machining	Annealing
7	0.25	4.00	44.0	Vertical	No	No
8	1.00	4.00	44.0	Horizontal	Machining	No
9	0.25	4.00	44.0	Vertical	Sand blasting	Annealing
10	1.00	4.00	44.0	Vertical	Sand blasting	No
11	1.00	2.99	12.3	Diagonal	Machining	Stress Relief
12	0.40	2.99	12.3	Vertical	No	Annealing
13	1.00	2.99	12.3	Diagonal	Sand blasting	No
14	0.85	2.99	12.3	Diagonal	Sand blasting	Annealing
15	0.25	4.00	1.7	Vertical	No	Stress Relief
16	0.25	4.00	1.7	Diagonal	Machining	No
17	0.25	4.00	1.7	Diagonal	No	Stress Relief
1	0.40	4.00	1.7	Vertical	Sand	Stress

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8					blasting	Relief
19	0.87	3.95	0.0	Horizontal	No	Stress Relief
20	0.25	3.95	0.0	Horizontal	No	No
21	1.00	3.95	0.0	Vertical	Machining	Annealing
22	1.00	3.95	0.0	Horizontal	No	Annealing
23	1.00	3.95	0.0	Diagonal	No	No
24	0.25	2.94	45.0	Horizontal	Machining	Annealing
25	0.25	2.94	45.0	Diagonal	Sand blasting	Stress Relief
26	0.87	2.94	45.0	Diagonal	No	No
27	0.25	2.94	45.0	Vertical	Machining	No
28	1.00	2.18	9.2	Horizontal	Machining	Annealing
29	0.78	2.18	9.2	Horizontal	Machining	No
30	1.00	2.18	9.2	Diagonal	No	Stress Relief
31	0.25	2.18	9.2	Horizontal	Sand blasting	Stress Relief
32	1.00	3.60	32.6	Horizontal	No	Stress Relief
33	1.00	3.60	32.6	Horizontal	Sand blasting	Stress Relief
34	0.25	3.60	32.6	Horizontal	Machining	Stress Relief
35	0.25	3.60	32.6	Horizontal	Sand blasting	No
36	1.00	3.60	32.6	Vertical	Machining	Stress Relief
37	0.25	2.00	0.0	Vertical	Machining	Annealing
38	0.25	2.00	0.0	Vertical	Sand blasting	No
39	0.40	2.00	0.0	Vertical	Machining	Stress Relief
40	1.00	2.00	0.0	Diagonal	Machining	Annealing
41	1.00	2.00	0.0	Vertical	Sand blasting	Annealing
42	1.00	2.00	29.8	Horizontal	No	No
43	1.00	2.00	29.8	Vertical	Sand blasting	Stress Relief
44	1.00	2.00	29.8	Vertical	Machining	No
45	0.58	2.00	29.8	Diagonal	Machining	Annealing
46	0.25	2.00	29.8	Horizontal	No	No

3.2 Designing, manufacturing and post manufacturing activities
The CAD model of the specimens was created using the SolidWorks program. The CAD file was uploaded on a fabricate web browser of Desktop Metal to set the print parameters.

This section is crucial as it evolves the study from the theoretical design phase to the practical implementation phase. It involves the actual creation of the stainless-steel specimens and the subsequent post-manufacturing activities that are integral to the process.

The manufacturing process is carried out using a specialized stainless-steel additive manufacturing machine. This machine uses a high-power laser to melt and fuse fine metallic powders into a three-dimensional structure. The machine builds the specimens layer by layer. This process ensures a high level of precision and repeatability, which is crucial for the validity of the experimental results.

After the specimens are manufactured, they undergo a surface finishing process. This process is important because the surface quality of the specimens can significantly influence their mechanical properties. Surface finishing can involve various techniques such as sanding, polishing, or blasting. Each of these techniques can alter the surface roughness of the specimens, which can affect properties such as friction, wear resistance, and fatigue strength. The choice of surface finishing technique depends on the specific requirements of the study.

The final step in the post-manufacturing process is heat treatment. This process involves heating the specimens to a specific temperature and then cooling them at a controlled rate. Heat treatment can alter the microstructure of the stainless steel, which can significantly affect its mechanical properties. For example, annealing can increase ductility and reduce hardness, while stress relief can reduce residual stresses without significantly altering the other mechanical properties. The specific heat treatment process used depends on the desired properties of the specimens [9].

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3.3 Mechanical testing and data collection

Performing tensile tests on all specimens after recording their weight. The mechanical tensile testing phase is a critical part of this study as it provides empirical data on the mechanical properties of the stainless-steel specimens. This phase involves subjecting each specimen to a tensile test after its weight has been accurately recorded. A tensile test, also known as a tension test, is a fundamental mechanical test where a sample is subjected to a controlled tension until failure. The purpose of this test is to measure the resistance of a material to a force that is trying to pull it apart. It provides fundamental information about the material, including its yield strength, ultimate strength, and ductility.

Recorded Results of each response as an average of 3 specimens for each experimental run are shown in table 3 below:

Table 3 Data collection for each experimental run

Runs	Responses				
	Response 1	Response 2	Response 3	Response 4	Response 5
	Tensile Strength (MPa)	Yield Strength (MPa)	Young's Modulus (GPa)	Strain (%)	Weight (g)
1	675	519	176	29.4	160.7
2	634	389	205	31.1	180.1
3	600	360	181	28.7	172.1
4	548	337	170	35.9	138.0
5	598	437	172	35.4	157.3
6	623	391	191	42.9	177.5
7	635	461	193	33.1	183.1
8	686	549	187	31.1	177.2
9	589	382	201	45.3	182.9
10	634	474	187	39.6	168.1
11	682	552	197	27.4	161.1
12	561	386	192	18.2	178.1
13	671	526	200	29.6	157.1
14	596	387	199	29.1	163.0
15	627	477	197	29.6	182.7
16	698	565	198	30.8	189.2
17	691	536	206	33.1	183.8
18	655	500	200	30.4	180.5
19	707	561	187	31	177.3
20	708	551	213	30.6	183.1
21	617	396	207	40.9	177.4
22	634	404	214	41.2	179.0
23	664	517	194	37.8	168.4
24	649	401	216	32	182.4
25	686	532	204	25.7	182.5
26	614	468	174	36.4	155.2
27	662	510	196	22.5	186.0
28	601	424	213	10	168.9
29	685	563	196	7.4	167.3
30	667	527	193	21.7	138.5
31	696	547	192	23.7	181.6
32	681	535	187	31.8	175.8
33	683	541	192	31.3	175.6
34	705	559	191	28.9	184.2
35	688	551	179	30.5	183.0
36	651	508	196	31.7	169.4
37	645	420	216	26.4	185.7
38	688	505	199	21.6	179.6
39	746	594	232	11.3	176.9
40	649	427	217	18.7	142.6
41	589	379	209	23.2	139.2
42	630	464	168	25.4	159.4
43	590	453	168	25.3	134.5
44	609	468	175	24.8	142.4
45	558	376	191	12.6	168.5
46	668	520	176	23.9	180.7

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3.4 Data Analysis:

3.4.1 General Statistics

Table 4 illustrates the type of experimental study of I-optimal response surface design with a quadratic model, comprising 46 runs. It's a split-plot subtype, indicating that different factors are applied to different parts of the experimental units. Blocks are unused in this design, suggesting that there are no distinct groups within the experimental structure. This design aims to efficiently explore the response surface while minimizing the average prediction variance of the estimated regression coefficients:

Table 4 type of experimental study

Study Type	Response Surface	Subtype	Split-plot
Design Type	I-optimal	Runs	46
Design Model	Quadratic	Blocks	No Blocks

Table 5 illustrates the general statistics of each factor separately. The range between min and max is essential in determining the targeted values of each variable in the upcoming optimization process for both the factors and responses in tables 5 and 6.

Table 5: Factors or independent variables of the experiment

Factor	Name	Type	Min.	Max.	Mean	Std. Dev.
A	Inner Cell Dimension	Numeric	0.2500	1.0000	0.6591	0.3452
B	Wall thickness	Numeric	2.00	4.00	2.96	0.8556
C	Inner Cells Orientation Angle	Numeric	0.0000	45.00	22.40	18.60
D	3D Printing Orientation	Categoric	Vertical	Diagonal	Levels:	3
E	Surface Roughness	Categoric	Machining	No	Levels:	3
F	Heat Treatment	Categoric	Stress Relief	No	Levels:	3

Table 6 illustrates the general statistics of each response separately.

Table 6: Responses or dependent variables of the experiment

Res	Name	Min.	Max.	Mean	Std. Dev.	Ratio	Transform
R1	Tensile strength	547.604	746.192	647.22	45.14	1.36	None
R2	Yield strength	337.295	593.961	476.71	69.80	1.76	None
R3	Youngs modulus	167.864	231.56	194.55	14.49	1.38	None
R4	Strain	7.4	45.3	28.46	8.29	6.12	None
R5	Weight	134.533	189.167	170.38	14.95	1.41	None

Since a ratio of max to min for a response of greater than 10 usually indicates that data transformation is required and as shown all ratios of responses are below 10 which indicate that no data transformation is required.

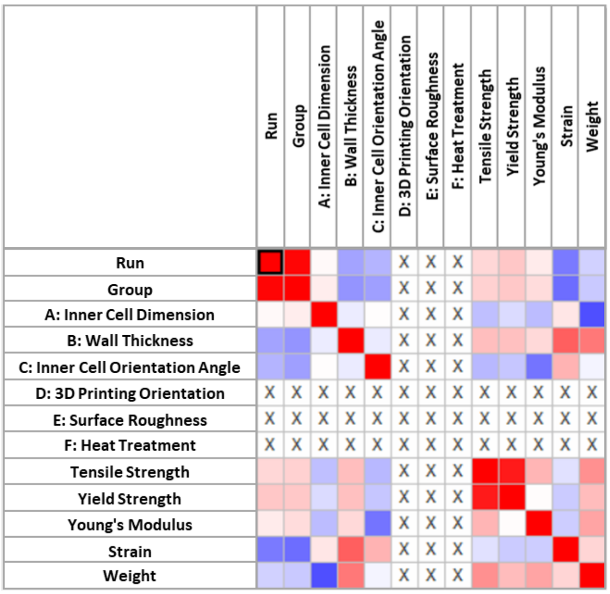

Figure 1: correlation matrix

Figure 1 shows the correlation matrix, the categorical factors are not represented by a value of correlation, meanwhile the numerical factors are represented.

Some observation after realizing the values presented in the matrix:

- Inner cell dimension has a weak negative correlation with yield strength and Young's modulus. This means that as the inner cell dimension increases, the yield strength and Young's modulus tend to decrease slightly.

- Wall thickness has a moderate positive correlation with tensile strength and yield strength. This means that as the wall thickness increases, the tensile strength and yield strength also tend to increase.
- Inner cell orientation angle has a weak negative correlation with tensile strength and Young's modulus. This means that as the Inner cell orientation angle changes, the tensile strength, yield strength and Young's modulus also tend to change slightly in the opposite direction.

3.4.2 Analysis of Variance (ANOVA)

Results of ANOVA are illustrated in Table 7 which reflect the statically significant factors that affect each response depending on P-values less than 0.05 and their F-Values are relatively high.

Table 7: ANOVA Table for all responses

Res	Source	Term df	Error df	F-value	p-value
Tensile Strength	Subplot	8	32.43	11.03	< 0.0001
	a-Inner Cell Dimension	1	32.32	11.15	0.0021
	C-Inner Cells Orientation Angle	1	19.85	9.82	0.0053
	D-3D Printing Orientation	2	34.77	9.08	0.0007
	E-Surface Roughness	2	35.41	5.62	0.0076
	F-Heat Treatment	2	36.32	27.23	< 0.0001
Yield Strength	Subplot	17	19.30	40.85	< 0.0001
	a-Inner Cell Dimension	1	25.41	15.36	0.0006
	C-Inner Cells Orientation Angle	1	17.26	31.68	< 0.0001
	D-3D Printing Orientation	2	24.68	27.08	< 0.0001
	E-Surface Roughness	2	26.35	15.02	< 0.0001
	F-Heat Treatment	2	27.38	262.24	< 0.0001
	BC	1	24.89	8.10	0.0087
	CE	2	27.01	3.42	0.0476
	EF	4	26.10	2.92	0.0404
Young`s modulus	Subplot	11	34.00	10.62	< 0.0001
	a-Inner Cell Dimension	1	34.00	7.79	0.0086
	C-Inner Cells Orientation Angle	1	34.00	44.41	< 0.0001
	E-Surface Roughness	2	34.00	3.36	0.0466
	F-Heat Treatment	2	34.00	4.74	0.0153
	BC	1	34.00	8.60	0.0060
	C^2	1	34.00	11.94	0.0015
Strain	Subplot	16	29.00	10.07	< 0.0001
	a-Inner Cell Dimension	1	29.00	6.85	0.0139
	B-Wall thickness	1	29.00	48.16	< 0.0001
	C-Inner Cells Orientation Angle	1	29.00	28.60	< 0.0001
	E-Surface Roughness	2	29.00	4.99	0.0137
	aD	2	29.00	4.34	0.0224
	BC	1	29.00	9.73	0.0041
	a^2	1	29.00	10.07	0.0036
	C^2	1	29.00	4.29	0.0474
Weight	Subplot	21	17.41	165.19	< 0.0001
	a-Inner Cell Dimension	1	19.72	1707.07	< 0.0001
	B-Wall thickness	1	18.80	200.09	< 0.0001
	D-3D Printing Orientation	2	23.44	32.81	< 0.0001
	E-Surface Roughness	2	20.87	40.69	< 0.0001
	F-Heat Treatment	2	20.80	8.59	0.0019
	aB	1	19.20	232.88	< 0.0001
	aD	2	19.81	99.27	< 0.0001
	BD	2	22.19	15.44	< 0.0001
	DE	4	22.17	6.99	0.0009
	EF	4	21.22	6.21	0.0018

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According to ANOVA wall thickness has no significant impact on the tensile strength, yield strength, and Young's modulus. While Inner Cells Orientation Angle has no significant impact on weight only. For 3D printing orientation, it has no significant impact on Young's modulus, and strain. For heat treatment, it has no significant impact on only the strain.

All non-significant factors had been excluded from the model to enhance the software analysis and to obtain the ANOVA table.

Table 7 judges that the following factors have no significant impact on specific responses based on the p-values since they were excluded from the model during the analysis:

- Wall thickness has no significant impact on tensile strength and yield strength.
- 3D Printing Orientation and wall thickness have no significant impact on Young`s modulus.
- 3D Printing Orientation and heat treatment have no significant impact on strain.
- Inner Cells Orientation Angle has no significant impact on weight.

4. RESULTS AND FINDINGS

The experiment was conducted to examine the mechanical properties and the effect of the independent variables on the dependent variables of the experiment which are defined as factors and responses.

4.1 Prediction of responses

The following surface plots show the impact of two factors on a single response. The representation of factors on the surface plot includes only the continuous numerical factors of the experiment which are:

a. Inner cell dimension

b. Wall thickness

c. Inner cell orientation angle

While the other categorical factors are not represented because they are discrete variables. However, on each plot only two independent variables are represented and the other four independent variables took an assigned value by the software as presented in table 8:

Table 8: Assigned values to independent variable by the software

No.	Independent Variable	Assigned Value
1	Inner Cell Dimension	0.625 mm
2	Wall thickness	3 mm
3	Inner Cells Orientation Angle	22.5 ◦
4	3D Printing Orientation	Vertical
5	Surface Roughness	Machining Surface Roughness
6	Heat Treatment	Stress Relief

These assigned values can be changed to further examine the model and have no statistical necessity to be valued as presented in the previous table. The aim of setting the values as presented is to analyze the impact of the factors on responses under similar conditions.

4.2 Tensile Strength Prediction

As shown in Figure 2, the tensile strength approaches higher values as the inner cell dimension approaches 0.25 and the wall thickness has no impact on tensile strength as it is a non-significant factor as discussed earlier in ANOVA.

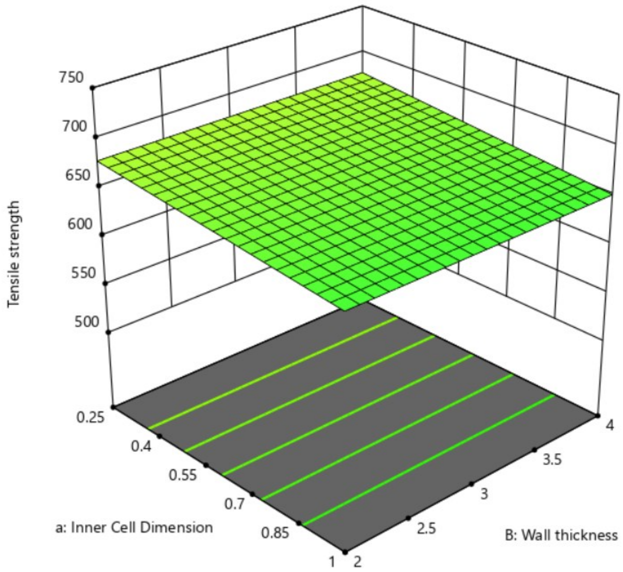

Figure 2: Surface plot of tensile strength under the effect of wall thickness and inner cell dimension

4.3 Yield Strength Prediction

As shown in Figure 3, yield strength approaches higher values as the inner cell dimension approaches 0.25 and the wall thickness has no impact on yield strength as it is a non-significant factor as discussed earlier in ANOVA.

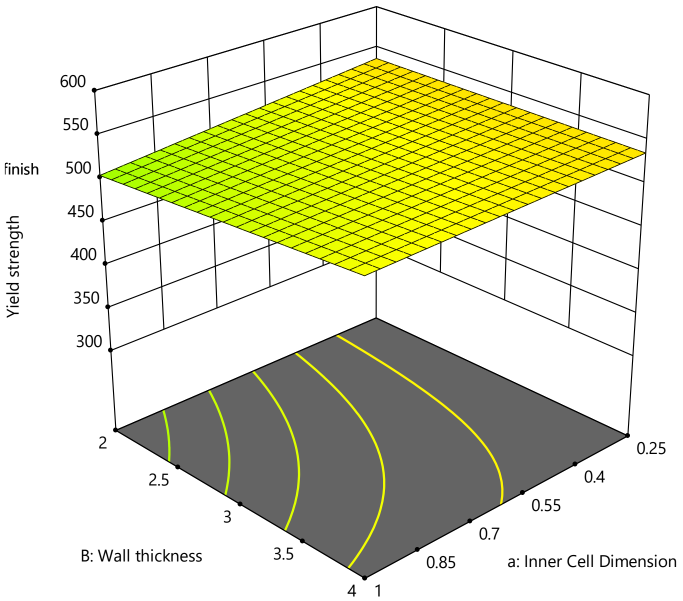

Figure 3: Surface plot of yield strength under the effect of wall thickness and inner cell dimension

4.4 Young's Modulus Prediction

As shown in Figure 4, Young's modulus approaches the higher values as the wall thickness is in between (2.5-3) and the inner cell dimension decreases.

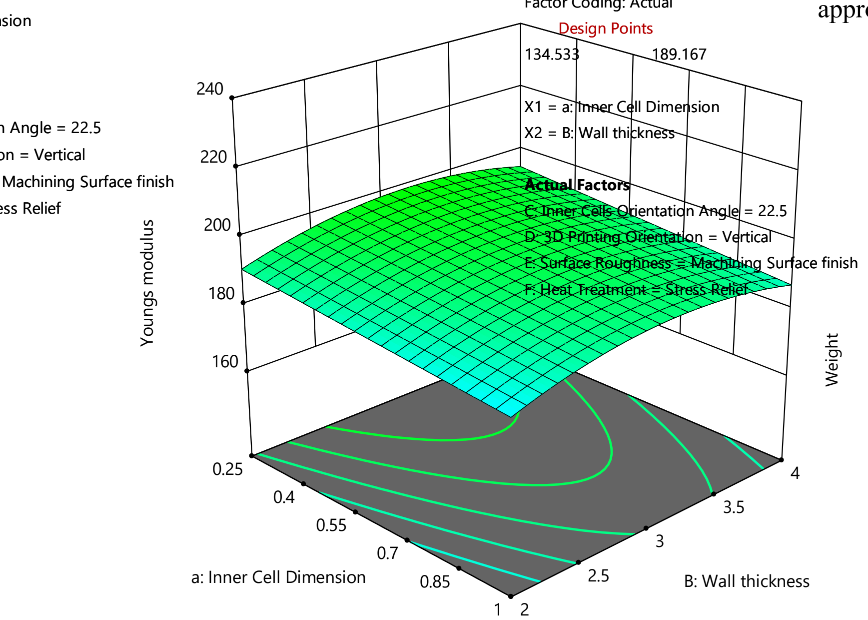

Figure 4: Surface plot of Young's Modulus under the effect of wall thickness and inner cell dimension

4.5 Strain Prediction

As shown in Figure 5, strain approaches higher values as the wall thickness increases and the inner cell dimension increases.

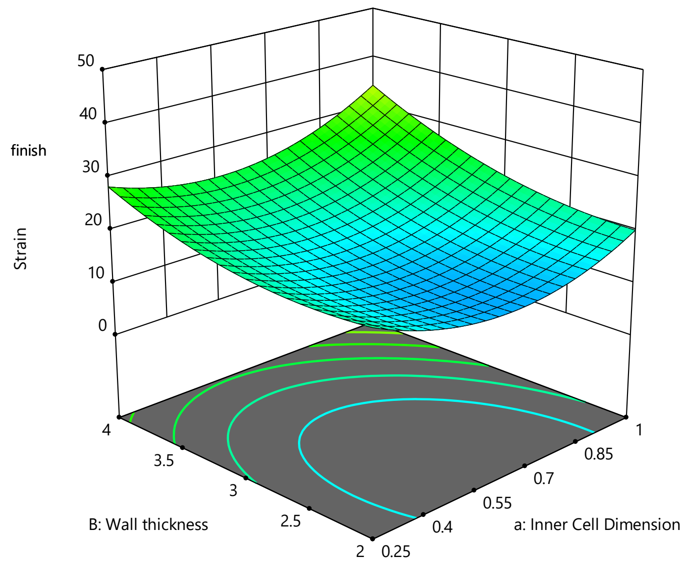

Figure 5: Surface plot of strain under the effect of wall thickness and inner cell dimension

4.6 Weight Prediction

As shown in Figure 6, weight approaches the minimum value as the wall thickness approaches 2 and the inner cell dimension approaches 1.

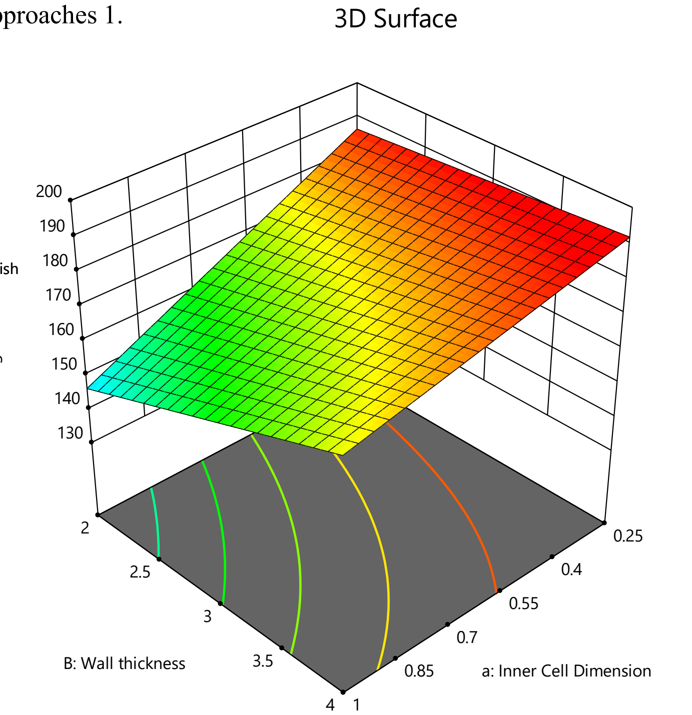

Figure 6: Surface plot of weight under the effect of wall thickness and inner cell dimension

4.7 Optimization

The aim of the experiment is to enhance and improve the status of the model, one of the improvement methods is to optimize the outputs. In the case of this study, the optimization of the outputs clears up the levels of the manufacturing and post-manufacturing activities.

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Taking into consideration that all inputs are in range and no specific values are required. The aimed outputs of the optimization are illustrated in table 9:

Table 9: the aim of each response in optimization

Response	Aimed Value
Tensile strength	Maximum
Yield strength	Maximum
Youngs modulus	In range
Strain	In range
Weight	Minimum

The results of the optimization which should be the inputs of the manufacturing process to reach the desired output values are illustrated in table 10:

Table 10: the optimization results for each factor

Factor	Aimed Value	Optimized Value
Inner Cell Dimension	In range	1
Wall thickness	In range	2
Inner Cells Orientation Angle	In range	0°
3D Printing Orientation	In range	Diagonal
Surface Roughness	In range	Machining Surface Fininshing
Heat Treatment	In range	Stress Relief

The outputs of the manufacturing process depending on the statistical analysis should be as illustrated in Table 11:

Table 11: the predicted values of the optimized manufacturing process

Variable Type	Name	Aimed Value	Optimized Value
Response	Tensile strength	Maximum	697.9
Response	Yield strength	Maximum	582.7
Response	Youngs modulus	In range	214.4
Response	Strain	Maximum	19.2
Response	Weight	Minimum	143.9

5.CONCLUSIONS

This study has successfully demonstrated the potential of using a structured cell approach in designing and manufacturing stainless-steel specimens to reduce their cost and weight.
This study has made significant strides towards achieving its goal of reducing the cost and weight of manufactured objects by partially evacuating the inner structure via an inner net of structured cells. The findings of this research have broad implications for the field of materials science and can inform future work on the design and manufacturing of lightweight, cost-effective stainless-steel components.

The results of this study provide a solid foundation for further experimental investigations. Future studies could explore different design parameters, manufacturing conditions, or material types to expand the understanding of the relationship between the inner structure of manufactured objects and their mechanical properties.
This study focused on the immediate mechanical properties of the specimens after manufacturing. Future research could investigate the long-term performance of the specimens, such as their fatigue strength or corrosion resistance.
The ultimate goal of this research is to reduce the cost and weight of manufactured objects. Future studies could focus on applying the findings of this research to real-world applications, such as the design and manufacturing of lightweight structures for the automotive or aerospace industries.

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