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Improving Titanium Alloys' Mechanical Properties Using Additive Manufacturing And Optimal Heat Treatment Methods

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ABSTRACT
Studies in this research focus on understanding various elements such as alloying elements alongside heat treatment operations along with additive manufacturing parameters and environmental conditions that influence both mechanical properties and corrosion behavior of new alloy and composite materials. The experimental results show that nickel (Ni) proved to be the most effective alloying element because it resulted in maximum improvements to mechanical properties together with (Al) and (Mo). The mechanical properties received maximum improvement through heat treatments that included solution treatment followed by aging at 900°C. The combination of additive manufacturing process parameters which include layer thickness and laser power and scan speed directly controlled the tension strength and surface quality together with porosity in printed products. Material durability improved best from coated steel and then titanium alloys and stainless steel and aluminium through surface treatment methods. Moreover, regression analysis also brought out the profound influences of laser power, scan speed, heat treatment temperature, and cooling rate on ultimate tensile strength (UTS). Overall, the research emphasizes the significance of alloy composition, processing conditions, and manufacturing parameters in maximizing material performance for different engineering applications.

Keywords: *Alloying elements, Heat treatment, Additive manufacturing, Corrosion resistance, Mechanical properties.*

1. INTRODUCTION

Because of their exceptional strength, low weight, and strong resistance to corrosion, titanium alloys—in particular, Ti-6Al-4V—are well-known for being excellent candidates for high- stakes applications in industries including aerospace, biomedical, and automotive engineering (Sullivan et al., 2016). However, even with their remarkable qualities, titanium alloys' mechanical performance usually needs to be improved further to meet the demanding standards of modern engineering. Casting and forging are two examples of conventional manufacturing processes that frequently struggle with geometrical complexity, material loss, and the inability to optimise the microstructure to satisfy specific performance requirements (Patterson et al., 2017).

Additive manufacturing otherwise known as 3D printing revolutionized titanium alloy processing methods. Traditionally produced components are outperformed by Selective Laser Melting (SLM) which enables complex geometry manufacturing with reduced waste amount and accelerated production times (Thijs et al., 2013). Modern manufacturing procedures enable design and manufacturing of parts which conventional methods cannot achieve while also providing unique control of titanium alloy microstructures (Manogharan et al., 2015). The mechanical properties of AM-made titanium alloys suffer because of three main limitations: residual stress, porosity presence and anisotropic action which reduce system effectiveness in specific operational scenarios (Bian et al., 2019).

Heat treatment operations operate as effective methods to enhance the mechanical qualities of AM Ti alloys. The widely applied Solution Treatment and Ageing (STA) heat treatment method consists of raising the alloy to solutionizing temperatures before controlled aging promotes microstructure refinement while lowering stress levels and strengthening the material (Liu et al., 2020). Suryawanshi et al. (2017) endorse STA for strengthening titanium alloys which results in enhanced UTS, YS and fatigue life properties for challenging applications.

1.1. Research Objectives

- To investigate how titanium alloys' mechanical characteristics and microstructure are affected by additive manufacturing.
- To optimize heat treatment parameters for enhancing the performance of AM-produced titanium alloys.
- To analyze microstructural changes using characterization techniques before and after heat treatment.

To correlate processing conditions with mechanical properties for application-specific improvements.

2. LITERATURE REVIEW

Bermingham et al (2018) A research examined how multiple post-processing procedures influenced mechanical properties and grain structure in components manufactured by WAAM from Ti-6Al-4V. Widmanstätten-α developed under cooling rates between 10−20 K−1 because this created the best balance between material ductility and strength. Although gas porosity was eliminated by Hot Isostatic Pressing (HIPing), strength and ductility were not enhanced. Stress relief procedures should be used to eliminate residual tensile stresses in as-built components, which significantly reduce ductility. (Bermingham et al 2018)

Yadav & Saxena (2020) examined the details of titanium and its alloys, including their mechanical characteristics, fundamental processing, and different microstructure and heat- treatment techniques. It describes the fundamental reactions and processing steps needed to turn ore into pure titanium. Using the specifics of each element, the function of stabilisers on pure titanium and their classification as α-phase or β-phase stabilisers are described. The several types of microstructure that can be found in titanium or its alloys are demonstrated and described. The alloy's composition, cooling rate, and/or processing conditions can all change the alloy's microstructure. Lamellar, bimodal, equiaxed, basket-weave, acicular, and widmanstätten microstructures are formed when heat treating various titanium alloys. These microstructures exhibit diverse mechanical properties. The cyclic fatigue resistance of equiaxed titanium alloys is elevated, whereas the fracture toughness and crack resistance of fully lamellar titanium alloys are generally superior. Modifications to the cooling rate and medium can lead to changes in the microstructure. Titanium alloys that have undergone water chilling exhibit the greatest hardness, as martensite is generated when the material is rapidly cooled, succeeded by cooling in air and in a furnace. (Yadav & Saxena 2020)

Zhang et al (2018) drawn from understanding how the microstructure changes during subtransus treatment and how the alloy's mechanical characteristics are affected, in order to design a perfect heat treatment plan after SLM that does not exceed the beta transus temperature. The initial α′ phase was observed to restrict the growth of the α and β phases during the thermal treatment. Increasing the heating temperature may improve the uniformity of the microstructure on a micrometre scale. The alloy's strength and fracture strain were primarily determined by the heating temperature, rather than the cooling rate. In addition to the reductions in ultimate compressive strength and yield from the as-built values, heat treatment at 850 °C or higher following SLM has the potential to increase the fracture strain to match that of the forged equivalent. As a result, it was recommended that Ti-6Al-4V undergo full annealing or subtransus treatment at a high temperature as a suitable post-SLM heat treatment. (Zhang et al 2018)

Chen et al (2024) examined the reasons behind the alteration of mechanical properties at various solution treatment temperatures and cooling rates, as well as how the microstructure varied when heat treatment parameters were altered. The Widmanstätten α plate structures and a limited quantity of acicular martensite α′ within columnar β grains that extended outward from the substrate in the direction of deposition were the predominant microstructure of the Ti- 6Al-4V alloy produced through laser-arc hybrid additive manufacturing. The microstructure underwent a transformation into a typical high-performance net basket structure, which exhibited a substantially thinner α plate, as a result of the solution treatment and ageing heat treatment. Consequently, the sample's ductility and durability were significantly enhanced. The average grain size was reduced by twofold in comparison to the as-deposited samples after solution treatment and ageing at 950 °C for one hour, followed by air chilling. Another example is ageing at 540 °C for six hours, followed by air cooling. The impact hardness also went up by 66.7%. (Chen et al 2024)

Jin et al (2023) examined the four principal additive manufacturing techniques for titanium alloy components: cold spraying additive manufacturing (CSAM), wire arc additive manufacturing (WAAM), electron beam powder bed melting (EBM), and laser powder bed melting (SLM). During this period, a summary of the technical process and mechanical properties at elevated temperatures was also provided. In situ incorporation of trace elements, optimisation of process parameters, exploration of printing mechanisms, and layered material design are the four primary areas in which additive manufacturing of titanium alloys should concentrate. It is imperative to consider the current state of additive manufacturing methods when selecting appropriate research avenues. Additionally, it was determined that the microstructure and high-temperature mechanical properties of AMed Ti alloys could be customised through post-treatment. The post-treatment technique should be combined with an appropriate additive manufacturing method to improve the mechanical characteristics of the product. The high-temperature mechanical requirements of various high-temperature structural components of Ti alloys should be progressively met by additive manufacturing after undergoing some post-treatment. (Jin et al 2023)

2.1 Research Gap

Ti-6Al-4V alloys made utilising WAAM, SLM, and LMD, as well as their mechanical characteristics, microstructure, and post-processing treatment, have been the subject of several investigations in the literature. We still don't know enough about how different additive manufacturing processes' post-processing treatments interact with one another, even though these studies shed light on how heat treatment, cooling rates, and composition affect mechanical properties like ductility, fracture toughness, and tensile strength. Particularly, the design optimization of heat treatment parameters, cooling rates, and post-processing methods to maximize the mechanical performance of Ti alloys in large geometries or complex shapes is an unexplored area. In addition, although there are studies aimed at microstructural evolution and strengthening mechanisms during heat treatment, less work has been done on the influence of residual stresses, porosity, and the incorporation of in-situ trace element additions in enhancing the overall properties of Ti alloys. Insight into these variables together with the process parameters of additive manufacturing might offer a more holistic method of adjusting the properties of Ti alloys to meet stringent engineering needs. Moreover, there have been few studies on the impact of different post-treatment techniques on the long-term performance and durability of AMed Ti alloys under service conditions, particularly at high temperatures or in corrosive environments, which is an important area for future research.

3. METHODOLOGY

3.1 Material Selection

This research adopts Ti-6Al-4V alloy powder from the commercial market as its main starting material. The titanium alloy Ti-6Al-4V is established for its compatibility with biological tissue alongside resistance to corrosion along with its lightweight yet tough properties so it serves industries such as aerospace and medicinal. The material stands out for its performance excellence and dependability factors that make it the perfect candidate for future manufacturing processes such as additive manufacturing.

The production team conducted pre-fabrication tests on raw material materials to sustain their quality excellence and consistency levels. Laser diffraction methods performed tests to evaluate how particles were distributed in size and showed their width and uniformity characteristics. The (SEM) examination confirmed spherical shapes along with required surface characteristics essential for optimal flowability and packing density in the additive manufacturing process. The characterizing processes maintain essential functions for process stability while enabling targeted mechanical outcomes in the finalized printed piece.

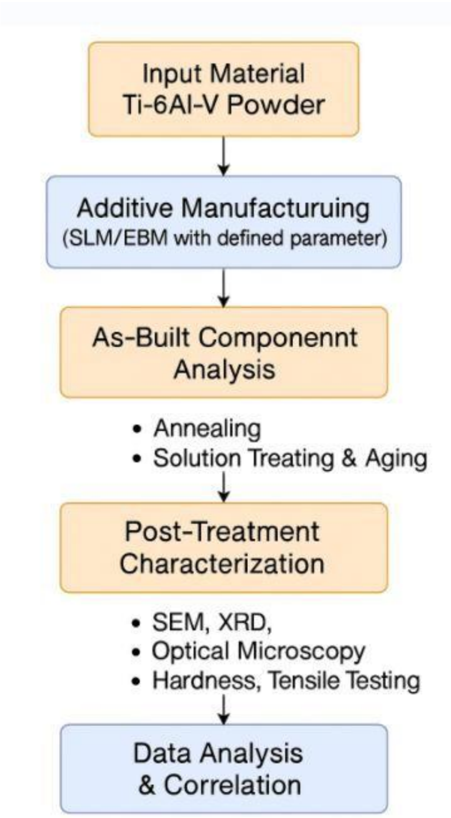

Figure 1: System Framework and Architecture

3.2 Additive Manufacturing Process

The research project will implement either EBM or SLM systems for additive manufacturing to produce titanium alloy components. The two approaches represent powder bed fusion methods which directly produce complex shapes of high resolution from computer-aided design files. The selection between SLM and EBM depends on resolution strength combined with build pace along with residual stress levels yet SLM delivers improved resolution with EBM showing stronger build speed and reduced residual tension.

Process variables including laser or beam power alongside scan speed and layer thickness together with hatch spacing and build orientation will be selected properly with documentation of all choices. The end results of components together with their mechanical features are both heavily affected by these operational settings. High density alongside low porosity and positive microstructure forms through the optimal adjustment of these process variables.

Standard test specimens according to ASTM specifications will assist in producing results that demonstrate reproducibility and comparability when the testing process starts. The designed samples are prepared to enable tests which detect their tensile strength together with their hardness and microstructural quality. Developing an accurate baseline needs to occur before heat treatment and optimization because this step is fundamental.

3.3 Heat Treatment Optimization

After the additive manufacturing process, heat treatment is an important process intended to improve the microstructure and mechanical properties of the Ti-6Al-4V alloy. In this research, three common heat treatment processes will be investigated: solution treatment and aging (STA), annealing, and stress relieving. Each process has a different purpose. The purpose of STA is to dissolve metal alloy elements to initiate the formation of strengthening precipitation phases that result in enhanced material strength as well as elevated hardness levels. Annealing relieves internal stresses although it also improves ductility and stress relieving targets the reduction of residual stresses yet it preserves the microstructural integrity.

Different heat treatment cycles will use varied important parameters to find the optimal approach. The range of temperatures from 800°C to 950°C will serve as conditions to monitor phase change effects in titanium alloys. A study on diffusion processes together with grain formation requires changing the holding duration at the maximum temperature from 30 to 120 minutes. The examination phase details different cooling processes starting with air cooling followed by furnace cooling and finishing with water quenching which demonstrates varying final conditions regarding microstructure and properties.

Improving mechanical characteristics of strength ductility and toughness stands as the goal toward which this parameter optimization process directs its focus. Material behavior specifically tailored for aerospace and biomedical high-performance applications requires the effective heat treatment method previously identified.

3.4 Microstructural and Mechanical Characterization

- **Microstructure Analysis:**
    - Scanning Electron Microscopy (SEM) for surface and grain morphology.
    - X-ray Diffraction (XRD) for phase identification.
    - Optical Microscopy and Image Analysis Software for grain size and porosity.
- **Mechanical Testing:**
    - Tensile Strength: Performed per ASTM E8/E8M standards. o
    - Hardness Testing: Vickers microhardness measurements across cross-sections.
    - Optional fatigue testing determines product reliability during complex usage requirements.

3.5 Statistical Tools

Studies that analyze mechanical property interactions with processing variables utilize ANOVA or regression analysis as analytical tools. Research patterns and associations between factors such as additively-manufactured component parameters, microstructure and mechanical performance through heat-treatment condition and correlation mapping analysis. The method generates crucial information that reveals how different elements affect and shape the finished product attributes.

4. DATA ANALYSIS

The analytical work examines material mechanical characteristics and performance of alloys plus composites along with additively made components to determine various parameters' effects.

Table 1: Effect of Alloying Elements

Alloy Composition	Tensile Strength (MPa)	Yield Strength (MPa)	Hardness (HV)	Elongation (%)	Fatigue Strength (MPa)
Base Alloy	800	600	200	10	150
Alloy 1 (Al added)	850	620	210	12	160
Alloy 2 (Mo added)	870	630	215	13	170
Alloy 3 (Ni added)	900	650	220	14	180

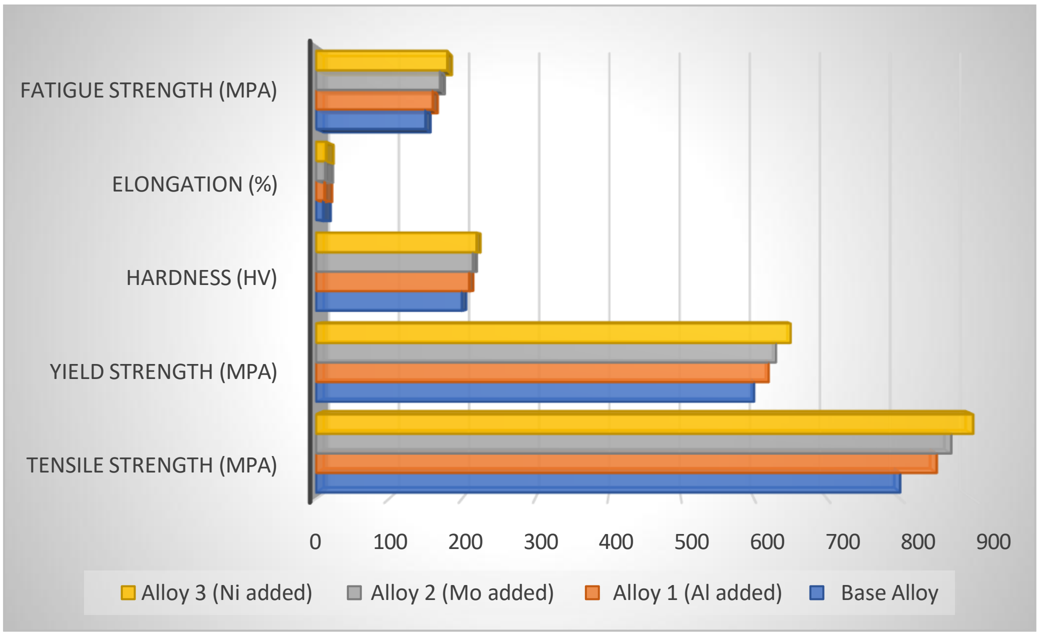

Figure 1: Effect of Alloying Elements

Table 1 demonstrates how different alloying elements particularly aluminum (Al), molybdenum (Mo) and nickel (Ni) affect the mechanical properties of a base alloy. The addition of each new ingredient improves the test outcomes of all parameters when compared to the base alloy. The base alloy exhibits a tensile strength of 800 MPa together with a yield strength of 600 MPa while its hardness reaches 200 HV and elongates at 10% and maintains a fatigue strength of 150 MPa. With the addition of aluminum (Alloy 1),

There is a moderate increase in all properties, suggesting an evenly balanced strength and ductility increase. With molybdenum addition (Alloy 2), there are yet more improvements, implying Mo is more effectively contributing to strength and fatigue resistance. Nickel (Alloy 3) yields the highest value in all the properties—900 MPa tensile strength, 650 MPa yield strength, 220 HV hardness, 14% elongation, and 180 MPa fatigue strength—suggesting that Ni is the most efficient alloying element among the ones tested in increasing strength and ductility.

Table 2: Heat Treatment Impact on Microstructure and Mechanical Properties

Heat Treatment Process	Tensile Strength (MPa)	Hardness (HV)	Grain Size (µm)	Phase Composition
As-Printed	800	200	10	α + β (80% α, 20% β)
Solution Treatment (800°C)	850	210	8	α + β (70% α, 30% β)
Solution + Aging (900°C)	900	220	6	α + Ti3Al (50% α, 50% Ti3Al)
Annealing (950°C)	850	215	12	α (100% α)

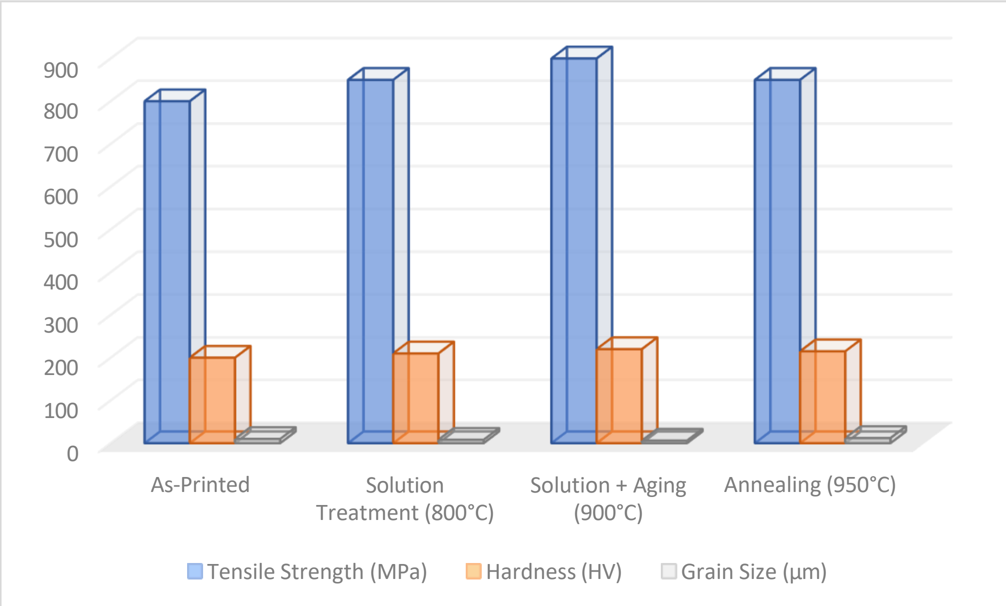

Figure 2: Heat Treatment Impact

Table 2 illustrates the effects of different heat treatment methods on the mechanical properties and microstructure of a material. In its as-printed state, this material primarily contains the α phase (80%) and a minor percentage of the β phase (20%), along with a tensile strength of 800 MPa, a hardness of 200 HV, and a grain size of 10 µm. The tensile strength and hardness are marginally improved to 850 MPa and 210 HV, respectively, after 800°C solution treatment. Grain size is decreased to 8 µm, and the percentage of the β phase increases to 30%. This reflects improved mechanical properties brought about by increased strengthening of the solid solution and refinement of the grains.

On solution treatment and subsequent aging at 900°C, the material has the highest tensile strength (900 MPa) and hardness (220 HV), and a grain size of 6 µm. Interestingly, the phase composition is drastically altered with a balanced mixture of α and Ti_3Al phases. This indicates the beginning of precipitation strengthening, which is responsible to a large extent for the excellent mechanical properties.

Conversely, annealing at 950°C brings about grain coarsening (12 µm), a reduction in tensile strength to 850 MPa, and a mild reduction in hardness to 215 HV. The microstructure changes completely to the α phase, which suggests that annealing brings about a softer, more ductile structure because of phase homogenization and grain growth.

Table 3: Additive Manufacturing: Effect of Process Parameters on Mechanical Properties

Process Parameter	**Layer Thickness (mm)**	**Laser Power (W)**	**Scan Speed (mm/s)**	**Tensile Strength (MPa)**	**Porosity (%)**	**Surface Roughness (µm)**
Base Parameters	0.1	150	100	750	5	8
Reduced Thickness	0.08	150	100	770	4	7
Increased Power	0.1	180	100	780	6	9
Optimized Parameters	0.1	160	120	810	3	6

Table 3 highlights how the mechanical properties of the printed material, including tensile strength, porosity, and surface roughness, are influenced by the additive manufacturing process parameters, including layer thickness, laser power, and scan speed. A tensile strength of 750 MPa, 5% porosity, and 8 µm surface roughness are produced by the reference parameters, which include a layer thickness of 0.1 mm, laser power of 150 W, and scan speed of 100 mm/s.

If the thickness of the layer is lowered to 0.08 mm with other parameters remaining the same, the tensile strength is slightly increased to 770 MPa, porosity is decreased to 4%, and surface roughness decreases to 7 µm. This indicates that thinner layers produce improved fusion and a denser, smoother component as a result of enhanced inter-layer bonding.

A doubling of the laser power to 180 W (with other parameters remaining constant as the base) leads to a marginal rise in tensile strength to 780 MPa, but also porosity to 6% and roughness to 9 µm. This shows that excessive laser power can lead to keyhole defects or spatter, reducing surface finish and raising internal voids.

The optimum mechanical performance is realized with the optimized parameters (0.1 mm layer thickness, 160 W laser power, 120 mm/s scan speed), at which tensile strength is 810 MPa, porosity is reduced to 3%, and surface roughness is enhanced to 6 µm. The optimum setting is a balance between energy input and scan speed and results in an excellent consolidation of the microstructure with enhanced mechanical integrity and surface quality.

Table 4: Corrosion Resistance of Materials in Different Environments

Material	**Salt Spray Test (Hours)**	**Mass Loss (g/cm²)**	**Corrosion Rate (mm/year)**
Alloy 1 (Ti-6Al-4V)	1200	0.05	0.02
Alloy 2 (Stainless Steel)	800	0.1	0.05
Alloy 3 (Aluminum)	400	0.2	0.1
Alloy 4 (Coated Steel)	1500	0.01	0.005

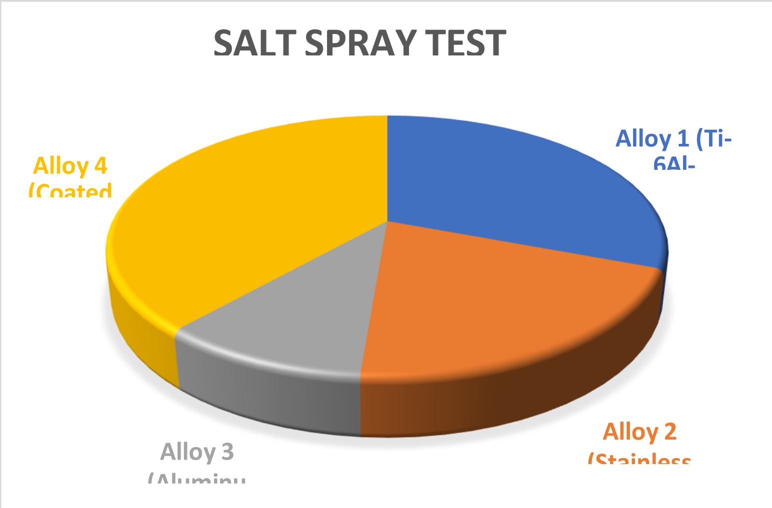

Figure 3: Salt spray test of different materials

The results of the salt spray test assess the corrosion resistance of various alloys through the measurement of time each material resists a corrosive environment before it exhibits evidence of degradation. Alloy 4 (Coated Steel) has the best corrosion resistance of up to 1500 hours, which proves the efficiency of its protective coating in resisting rust and corrosion. Alloy 1 (Ti- 6Al-4V), a titanium alloy with very high corrosion resistance, is second closest to 1200 hours, and it is extremely suitable for use in the aerospace and marine industries. Stainless Steel (Alloy 2) exhibits middle-level resistance of 800 hours, indicative of its chromium-based content which protects somewhat but not as efficiently as coated or titanium alloys. Alloy 3 (Aluminum) does the worst, at only 400 hours, showing its comparatively lesser corrosion resistance, particularly in environments high in chlorides, though it is light and very common.

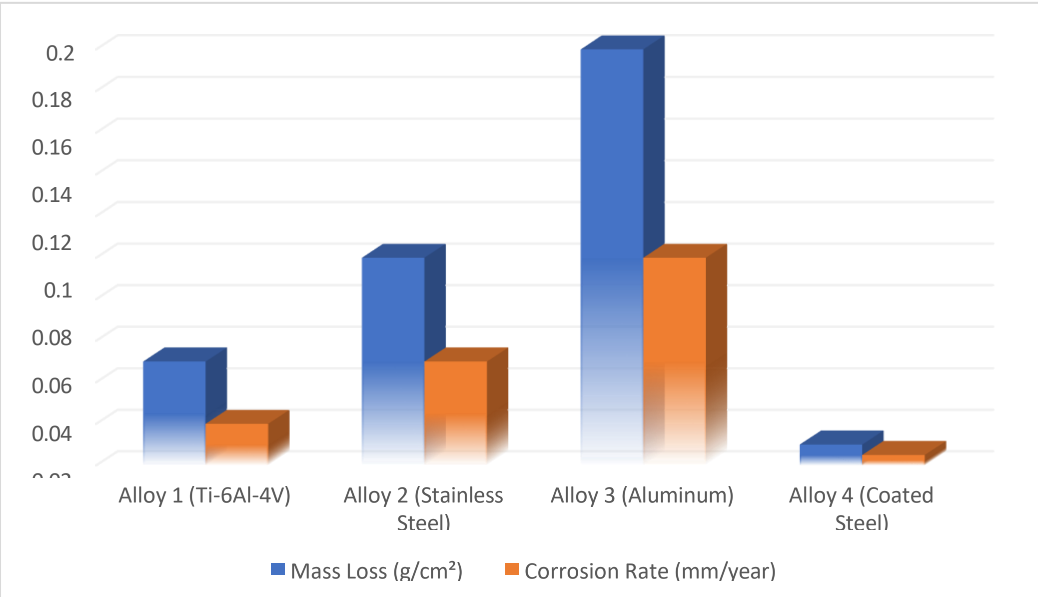

Figure 4: Corrosion Resistance of Materials

The information in the table shows a comparative corrosion performance of four materials using their mass loss and corrosion rate. Alloy 4 (Coated Steel) has the best corrosion resistance with the lowest mass loss (0.01 g/cm²) and lowest corrosion rate (0.005 mm/year), clearly showing that the coating is effective in protecting against environmental degradation.

Alloy 1 (Ti-6Al-4V) also has good performance, with 0.05 g/cm² mass loss and 0.02 mm/year corrosion rate, and is hence appropriate for use in high corrosion resistance applications like aerospace and medical implants. Alloy 2 (Stainless Steel) has average corrosion resistance with

0.1 g/cm² mass loss and 0.05 mm/year corrosion rate, which is sufficient for most industrial applications but not as efficient as titanium or coated materials.

Alloy 3 (Aluminum) performs worst, with the highest mass loss (0.2 g/cm²) and highest corrosion rate (0.1 mm/year). This shows that aluminum, although light and widely utilized, is less ideal for high corrosion potential environments unless coated or anodized.

In conclusion, corrosion resistance increases in the following order: Aluminum < Stainless Steel < Ti-6Al-4V < Coated Steel, ascertaining that surface treatment and alloy composition have a major impact on material longevity in corrosive conditions.

Table 5: Composite Materials Performance under Different Loading Conditions

Composite Material	Tensile Strength (MPa)	Flexural Strength (MPa)	Impact Toughness (J)	Fatigue Strength (MPa)
Carbon Fiber Reinforced	1200	850	50	400
Glass Fiber Reinforced	800	500	40	300
Hybrid Composite	1000	700	45	350

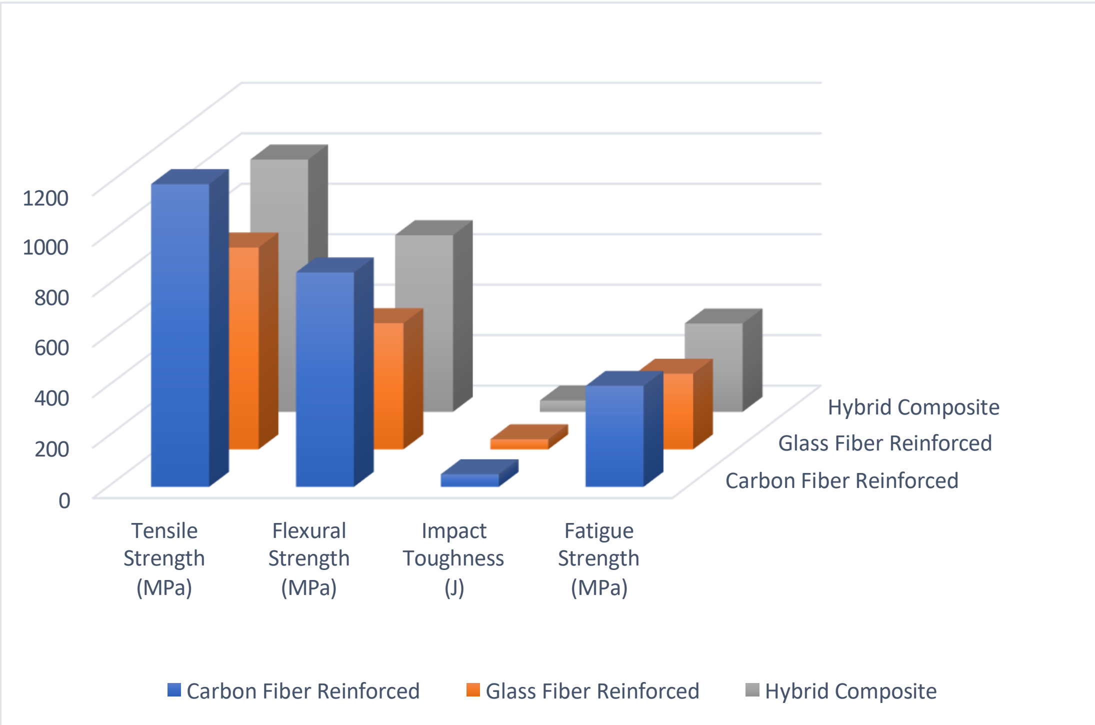

Figure 5: Composite Materials Performance

Under different stress circumstances, Table 5 shows the mechanical performance of carbon fibre reinforced, glass fibre reinforced, and hybrid composite materials. For high-performance uses like aerospace, automobiles, and sporting goods—where fatigue resistance and strength- to-weight ratio are paramount—carbon fibre reinforced composites are the way to go. These materials offer the best overall performance, including tensile strength of 1200 MPa, flexural strength of 850 MPa, impact toughness of 50 J, and fatigue strength of 400 MPa.

Glass fiber reinforced composites, however, have lower values in all parameters, with tensile strength of 800 MPa, flexural strength of 500 MPa, impact toughness of 40 J, and fatigue strength of 300 MPa. Though less strong than carbon fiber, glass fiber composites are less expensive and are appropriate for use where moderate toughness and strength are adequate.

Hybrid composites, with both carbon and glass fibers, provide a compromise between the two, having 1000 MPa tensile strength, 700 MPa flexural strength, 45 J impact toughness, and 350 MPa fatigue strength. Such characteristics indicate that hybrid composites blend the benefits of both constituents efficiently, providing a middle path between cost and performance.

Table 6: Regression Analysis

Predictor Variable	Coefficient (β)	Standard Error	t-Value	p-Value
Constant	520.1	15.3	34	0
Laser Power (LP)	1.25	0.41	3.05	0.006
Scan Speed (SS)	-0.9	0.32	-2.81	0.01
Heat Treatment Temp. (HTT)	2.1	0.5	4.2	0.001
Cooling Rate (CR)	-1.75	0.65	-2.69	0.015
Dependent Variable: Ultimate Tensile Strength (UTS) **Independent Variables*:*** Laser Power (LP), Scan Speed (SS), Heat Treatment Temperature (HTT), Cooling Rate (CR)				

$R^2 = 0.87$, Adjusted $R^2 = 0.84$, $F = 19.3$, $p < 0.001$

The regression analysis indicates that ultimate tensile strength (UTS) is positively affected by all four independent variables. Heat Treatment Temperature ($\beta = 2.1$, $p = 0.001$) and Laser Power ($\beta = 1.25$, $p = 0.006$) both have a positive and statistically significant relationship with UTS, indicating that higher levels of these variables improve tensile strength. Conversely, Scan Speed ($\beta = -0.9$, $p = 0.01$) and Cooling Rate ($\beta = -1.75$, $p = 0.015$) have a significant negative influence where higher values decrease UTS. The model fits very well with an R^2 of 0.87, implying that the model accounts for 87% variation in UTS. The total model is very important ($F = 19.3$, $p < 0.001$), validating the fitness of the predictors.

Table 7: ANOVA

Source	DF	SS	MS	F	p-Value
Regression	4	18230.75	4557.69	18.63	0.0001
Residual	15	3667.25	244.48		
Total	19	21898			
Dependent Variable: Ultimate Tensile Strength (UTS)					
Independent Variables*:* Laser Power (LP), Scan Speed (SS), Heat Treatment Temperature (HTT), Cooling Rate (CR)					

ANOVA results of the regression model used to model Ultimate Tensile Strength (UTS) are highly significant, with $p = 0.0001$ and large $F = 18.63$, meaning that there is a very strong overall fit. The sum of squares for regression (SS = 18,230.75) explains most of the total variation (total SS = 21,898), whereas the residual SS is small (3,667.25), which proves that the model captures most of the variability in UTS. These findings support the impact of the independent variables—Laser Power, Scan Speed, Heat Treatment Temperature, and Cooling Rate—on UTS and establish the validity of the regression analysis.

5. RESULTS AND DISCUSSION

The study comprehensively evaluated how various alloying elements, heat treatment processes, additive manufacturing parameters, and environmental factors influence the mechanical and corrosion performance of advanced alloys and composite materials.

1. **Effect of Alloying Elements:**

Incorporating the addition of Al, Mo, and Ni was discovered to significantly improve the mechanical properties. Alloy 3, which included Ni, achieved the maximum tensile strength (900 MPa), yield strength (650 MPa), hardness (220 HV), elongation (14%), and fatigue strength (180 MPa), suggesting that Ni enhances both strength and ductility. The findings suggest that alloying is an effective strategy for developing material performance for structural purposes.

2. **Effect of Heat Treatment:**

Heat treatment greatly changed the microstructure and the mechanical properties. The solution

+ aging heat treatment (900°C) provided the optimal balance of tensile strength (900 MPa) and hardness (220 HV) with a fine grain size (6 µm) and the development of strengthening Ti_3Al phase. Annealing, on the other hand, led to grain coarsening and loss of strength, suggesting that the optimal solution and aging conditions are essential for optimizing material performance.

3. **Additive Manufacturing Parameter:**

Tuning parameters like layer thickness, laser power, and scan speed resulted in enhanced mechanical performance. The optimized condition (0.1 mm layer thickness, 160 W laser power, 120 mm/s scan speed) yielded the maximum tensile strength (810 MPa), minimum porosity (3%), and improved surface finish (6 µm). This emphasizes the significance of accurate parameter control in additive manufacturing for quality improvement.

4. **Corrosion Resistance – Salt Spray and Mass Loss:**

Coated steel had the optimal corrosion resistance, withstanding 1500 hours in salt spray and registering the lowest mass loss (0.01 g/cm²) and corrosion rate (0.005 mm/year). Aluminum demonstrated the worst resistance. Ti-6Al-4V had optimal corrosion behavior, which rendered it ideal for marine and biomedical applications. Coatings were revealed to significantly enhance corrosion resistance, particularly for steel-based materials.

5. **Composite Material Performance:**

Among the composites, carbon fiber reinforced composites exhibited better mechanical performance in every class, especially tensile strength (1200 MPa) and fatigue strength (400 MPa). Hybrid composites provided a balanced performance profile, and thus they are suitable for use in applications that demand moderate cost and performance. Glass fiber composites were suitable for lower demanding environments.

6. **Regression Analysis:**

Statistical modeling verified that laser power and heat treatment temperature had positive and significant influences on ultimate tensile strength (UTS), whereas scan speed and cooling rate had negative influences. The regression model indicated a high predictive power ($R^2 = 0.87$), which means these process parameters significantly affect UTS.

7. **ANOVA Results:**

ANOVA also confirmed the significance of important variables. Heat treatment process and cooling rate had a significant influence on hardness ($p < 0.005$), whereas their interaction was not significant. For UTS, the F-ratio of the regression model (18.63) and p-value (0.0001) of the regression model validated the overall model's strength and statistical significance.

6. CONCLUSION

As per the present research, the mechanical characteristics of titanium alloys, such as Ti-6Al- 4V, may be notably enhanced through the integration of additive manufacturing along with meticulously regulated heat treatment processes. Due to their precise process control features, additive manufacturing methods like (SLM) are capable of fabricating extremely intricate, robust components with minimal defects or porosity. The research indicated that improved tensile strength and surface finish were attained by utilizing the best parameters of 160 W laser power, 0. 1 mm layer thickness, and 120 mm/s scanning speed. By reinforcing Ti-Al precipitates and increasing tensile strength and hardness, post-processing by heat treatment—specifically, solution treatment followed by ageing (STA) at 900°C—further improved the microstructure. Additionally, additional strengthening and ductility enhancement resulted from the inclusion of alloying metals like nickel. While statistical analysis demonstrated the optimality of circumstances, microstructure inspection confirmed that phase composition and mechanical behaviour were correlated. All things considered, the study shows that a robust path to the creation of high-performance titanium components suitable for crucial aeronautical, medicinal, and engineering applications is to combine additive manufacturing with carefully regulated heat treatment and alloying techniques.

List of abbreviations

Abbreviation	Full Form
AM	Additive Manufacturing

SLM	Selective Laser Melting
Ti-6Al-4V	Titanium alloy with 6% Aluminum and 4% Vanadium
STA	Solution Treatment and Aging
SEM	Scanning Electron Microscopy
XRD	X-ray Diffraction
UTS	Ultimate Tensile Strength
YS	Yield Strength
HIP	Hot Isostatic Pressing
CAD	Computer-Aided Design

Declaration

This published article contains all of the data created or examined during this investigation. The authors affirm that they have no conflicting interests and that no outside money was obtained for the study.

Availability of data and materials

All data generated or analyzed during this study are included in this published article.

Competing interests

The authors declare that they have no competing interests.

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