



RESEARCH ARTICLE

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A COMPREHENSIVE EXPERIMENTAL AND MULTI-CRITERIA DECISION-MAKING FRAMEWORK FOR OPTIMIZING SS316/TI6AL4V POWDER METALLURGY COMPOSITES

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ARTICLE INFO

Article History

Received: February 27, 2026

Reviewed: March 27, 2026

Accepted: April 01, 2026

Published: May 29, 2026

Keywords:

Sintering,
Density,
Mechanical properties,
ANOVA,
MARCOS

ABSTRACT

The development of austenitic stainless steel-based matrix composites with powder metallurgy were attracting interest for many uses in the aerospace and defense sectors. The influence of sintering temperature (1100, 1200, and 1300 °C), compaction pressure (550, 650, and 750 MPa), Ti6Al4V content (5, 7, and 9wt%), and sintering duration (45, 90, and 135 minutes) on the density, hardness and compressive strength of SS316/Ti6Al4V composites was evaluated utilizing Taguchi, ANOVA, and response surface methodologies. The research employed L9 OA based on Taguchi method. The composite powder were compressed using single-action die subsequently sintered at muffle furnace. The Simultaneous Evaluation of Criteria and Alternatives (SECA) approach was employed to obtain the significance of criteria for performance assessment. According to SECA analysis, the density of 0.1592, the hardness of 0.1363, and the compressive strength of 0.1347 was obtained. The application of MARCOS for ranking evaluation indicates that composite reinforced with Ti6Al4V demonstrated the most advantageous physical and mechanical properties. The verification of ranking through several decision-making confirms the efficacy and reliability of suggested method. The S/N ratio-based Taguchi approach identified the optimal input parameters, whereas ANOVA evaluated the individual contribution percentage of all factors. The response surface methodology was employed to assess contour plots, surface plots and regression equations for response qualities. The ANOVA results indicated that compaction pressure significantly influenced the properties of the fabricated composites, followed by the percentage of Ti6Al4V, sintering time, and sintering temperature, in that order. The results of the SECA-MARCOS approach demonstrate that the formulation with 7 wt.% Ti6Al4V is the most advantageous for defense and aerospace applications. Consequently, the formulated models of response qualities for costly trial tests, thereby enhancing the diminishing production costs and efficiency of the optimization process.



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I. INTRODUCTION

Matrix composites based on stainless steel are in high demand within the defense and aerospace sectors. This were due to their highly sought-after attributes, which encompass exceptional strength, lightweight composition, corrosion resistance, adequate wear resistance, stiffness and reduced cost relative to traditional stainless steel. A356 composites with nano-alumina were produced by powder metallurgy and forging techniques. Increased sintering temperature and finer alumina decreased porosity and enhanced hardness. Augmented diffusion increased density, whereas elevated temperature facilitated grain coarsening [1]. 316L stainless steel augmented with 1–5 vol% Ti and sintered at 1380 °C, exhibited enhanced densification and the production of β -Ti.

The optimal compromise was 3 vol% Ti at 1380 °C, resulting in a high density of 96.1%, an ultimate tensile strength of approximately 433 MPa, and commendable wear resistance. A low modulus of 58.9 GPa at 5 vol% Ti underscores its appropriateness for biomedical implant applications [2]. Ti-Mn alloys with minor Sn additions were fabricated by powder metallurgy to improve the strength-ductility equilibrium. Sn reduced the melting point and enhanced densification in Ti-2Mn alloys, resulting in refined α/β phases, increased ductility (15.9%), a strength of 784 MPa, and improved corrosion resistance. In Ti-4Mn alloys, Sn induced β -phase coarsening and impeded densification, hence diminishing performance enhancements [3]. The Ti-16Nb-4Sn alloy was synthesized using powder metallurgy, exhibiting a predominant β -phase structure alongside a minor α -phase. Elevating sintering temperature and duration diminished porosity and enhanced compressive strength. The elastic modulus approximated that of normal bone, rendering the alloy appropriate for biomedical implants without inducing stress shielding [4]. The TA15 alloy was produced by Spark Plasma Sintering (SPS) with the sintering temperature predominantly dictating the microstructure, while pressure exerted no effect. Increased temperature and duration enhanced densification, resulting in optimal mechanical performance at 900 °C, 50 MPa, and 5 minutes. The incorporation of 0.5% graphene further improved yield and compressive strength at both ambient and elevated temperatures [5]. Ti-Zr alloys were sintered using SPS utilizing

Ti and ZrH₂ powders, with homogeneous Zr dissolution attained at temperatures of 1000 °C or higher. Hardness augmented with temperature; nevertheless, excessive grain formation at 1200 °C diminished strength. The ideal sintering temperature was determined to be 1000 °C, achieving a balance between solid-solution strengthening and microstructural stability [6]. MgB₂/SS316L superconducting wire was produced by in-situ packing, sintering, and hot rolling processes. An elevated sintering temperature and extended holding duration enhanced superconducting transition and diminished porosity. Optimal performance was achieved at 800–820 °C with a sintering duration of 1–3 hours [7]. The WAAM-CMT process of SS308L was assessed utilizing the Taguchi L9 orthogonal array to investigate the impacts of current, welding speed, and gas flow on ultimate tensile strength, microhardness, residual stress and elongation. The Fuzzy AHP-MARCOS method determined the ideal parameters to be 140 A, 8 mm/s, and 16 L/min, with current as the predominant influence. XRD and EDX analyses verified that the optimally manufactured samples corresponded to the composition of industrial stainless steel [8]. Fe-based composites reinforced with nano-sized carbides and borides (B₄C, Fe₂B, Fe₇C₃, TiB₂) were fabricated using mechanical alloying and subsequently sintered at 1100 °C for 2 hours. Elevating B₄C concentrations diminished the particle sizes of TiC and TiB₂ while augmenting the TiB₂ content, resulting in a reduction of hardness owing to its comparatively softer characteristics.

Microstructural investigations revealed alterations in void concentration and stiffness corresponding to different reinforcement ratios [9]. A WC-6.4Fe-3.6Ni hard metal was produced using spark plasma sintering as a substitute for WC-Co. Elevated sintering temperatures (up to 1300 °C) enhanced densification and hardness (~1633 HV) but diminished toughness because to a smaller mean free path of the binder. The Fe-Ni binder improved wettability and diffusion, resulting in attributes that are competitive with traditional WC-Co grades [10]. Ti-15Nb-25Zr-(0–8) Fe alloys were sintered by SPS at temperatures ranging from 800 to 1200 °C to investigate phase evolution and mechanical properties. Elevated temperatures facilitated the development of the β -phase, resulting in increased strength (up to 1604 MPa) alongside favorable flexibility (~35%). Moderate iron addition (4%) enhanced diffusion and strengthening, but excessive iron (8%) resulted in intermetallic formation and grain coarsening, hence diminishing overall performance [11]. Fe-based composites reinforced with Ti, Ni₃Al, and Al₂O₃ were fabricated using mechanical alloying and subsequently sintered at 1000 °C for 1 hour. Nanocrystalline nickel-rich solid solutions with crystallite dimensions of several nanometers were synthesized. The incorporation of titanium enhanced microhardness, and phases including Fe₃Al, TiAl, NiAl, Al₃Ni₂, Al₂O₃, and Fe₃O were discovered [12]. The research investigates the melting of copper and its infiltration into iron-based matrices during sintering, enhancing interfacial diffusion. Liquid-phase copper improves adhesion at particle interfaces, fortifying typically vulnerable areas in powder compacts.

Enhanced diffusion at elevated temperatures and prolonged sintering durations results in substantial improvements in mechanical and physical characteristics [13]. Ti-35421 alloys underwent hot pressing, and the influences of temperature, pressure, and duration were assessed. The sintering temperature was the primary factor influencing density, secondary α -phase dimensions, and mechanical characteristics. Optimal circumstances (900 °C, 45 MPa, 2 h) resulted in a yield strength of 1248 MPa and a strain of 23%; nevertheless, elevated temperatures led to grain development and diminished strength [14]. Zirconia coatings were deposited on TC4 titanium alloy via discharge plasma sintering to enhance tribological performance. Increased sintering temperatures improved coating density, adhesion, and hardness, with optimal wear performance achieved at 1500 °C for 20 minutes. Enhanced diffusion at increased temperatures decreased friction (0.33) and wear rate due to augmented interfacial bonding [15]. A pseudo quasi in-situ technique was employed to investigate pore evolution, grain growth, and phase fractions in MIM-sintered Ti-6Al-4V alloys. Elevated sintering temperatures expedited pore elimination and grain coarsening, dictated by an activation energy of 252.2 kJ/mol. The optimal mechanical parameters (922 MPa strength, 12.8% elongation) were achieved at 1200 °C for 4 hours with little porosity [16].

FeNiCoCr HEA components produced using binder jet 3D printing exhibited an increase in density (78–98%) during sintering at temperatures ranging from 1410 to 1440 °C, resulting in the formation of a singular FCC phase. Hot Isostatic Pressing (HIP) markedly enhanced strength and ductility solely when the original sintered density surpassed 91%. The 1440 °C + HIP sample attained around 99.4% density, exhibiting elevated mechanical characteristics and corrosion resistance surpassing that of 316L stainless steel [17]. Mullite/kaolinite hollow fiber membranes reinforced with 0–12 wt% SS316L exhibited a significant enhancement in bending strength, increasing from 32 to 80 MPa. A balanced structure was achieved at 10 wt% SS, exhibiting commendable strength (66.7 MPa), 29% porosity, and 96.9% oil–water rejection. The optimized fibers shown significant potential for water treatment owing to improved strength and permeability [18]. The research assesses Ti6Al4V composites augmented with dual-ceramic ZrO₂–Si₃N₄ particles by Spark Plasma Sintering at 900 °C. All samples exhibited significant densification (~96.65%) and enhanced nanomechanical characteristics. The minimal ceramic content (S1) yielded optimal hardness, elastic modulus, and nano-hardness, but increased ceramic proportions diminished density and performance [19]. Ti6Al4V/TiCp nanocomposites were synthesized using Spark Plasma Sintering (SPS) at temperatures ranging from 1050 to 1160 °C, incorporating various concentrations of TiC. FE-SEM and XRD revealed dense, poreless microstructures with uniformly distributed TiC particles.

Elevating TiC concentration resulted in the formation of new phases and significant alterations in microstructure and mechanical properties [20]. The research examines the impact of porosity on the mechanical and acoustic properties of Ti-6Al-4V, engineered to replicate human bone. Increased porosity reduced the elastic modulus, elastic constants, and surface acoustic wave velocities as a result of structural phase transitions. The porous alloys exhibited enhanced mechanical-acoustic performance relative to cortical and cancellous bone [21]. Ti6Al4V–ZrO₂–Si₃N₄ composites were synthesized by Spark Plasma Sintering (SPS) at temperatures ranging from 950 to 1200 °C to investigate the influence of temperature on densification and nanomechanical properties. Properties its raised from 950 °C to 1100 °C, but decreased at 1200 °C, indicating a non-linear development. The optimal performance was observed at 1100 °C, attaining maximum hardness, and elastic modulus, with all samples sustaining over 95% relative density [22]. The novelty of this study lies in formulating a unified experimental–computational framework for optimizing SS316/Ti6Al4V powder metallurgy composites through an integrated Taguchi–SECA–MARCOS approach.

Unlike previous studies that examine individual PM parameters or rely on single-objective optimization, this work simultaneously evaluates the influence of four critical factors—Ti6Al4V content, compaction pressure, sintering temperature, and sintering duration—on density, hardness, and compressive strength. A comparative multi-criteria evaluation was performed using MARCOS and benchmarked against established MCDM methods such as ARAS, WASPAS, MOORA, and COPRAS to validate ranking stability and methodological consistency. The inclusion of SECA further provides objective weighting of the performance criteria, enabling a more rigorous assessment of parameter significance. This combined optimization and comparative analysis technique successfully identifies the optimal reinforcement level and processing parameters for achieving low-density, high-strength SS316/Ti6Al4V composites, offering a robust pathway for advanced material design in aerospace and defense applications.

II. MATERIALS AND METHODS

SS316 stainless steel powder (45 µm, 99.5% purity) served as the matrix material and was obtained from Matrics Enterprises, Nagercoil, Tamilnadu, India. Ti6Al4V alloy powder (<45 µm) was chosen as the reinforcement owing to its elevated specific strength and compatibility with Fe-based matrices, purchased from same Matrics Enterprises. The characteristics of both powders were presented in Table 1. Table 2 displays the chemical composition of SS316. The SS316 and Ti6Al4V powders were amalgamated at a 10:1 ball-to-powder ratio, 200 rpm speed, and a milling duration of 2 hours to ensure homogenous mixing. The necessary powder amounts were measured using a digital balance. The composite powders were compressed into cylindrical pellets of 10.5 mm in height and 13 mm in diameter utilizing a single-action die and a hydraulic press (EIE Instruments, 1000 kN). Three compaction pressures were established: 550, 650, and 750 Mpa. The green compacts were sintered in an argon-controlled high-temperature furnace at 1100 °C, 1200 °C, and 1300 °C for durations of 45, 90, and 135 minutes, chosen to facilitate solid-state diffusion and densification of the SS316/Ti6Al4V system.

Table 1: Characteristics of SS316 and Ti6Al4V.

Material	Type	Melting point, (°C)	Hardness (HB500)	Compressive strength, (Mpa)	Elastic modulus, (Gpa)	Density, (g/cc)
SS316	Alloy	1375	150	1700	193	7.9
Ti6Al4V	Ceramic	11200	330	1100	110	4.43

Source: Authors, (2026).

Table 2: Chemical composition of Stainless steel SS316.

Elements	Cr	Ni	Mo	Mn	Si	C	P	S	N	Fe
%	16	10	2	2	0.75	0.08	0.045	0.03	0.10	Bal

Source: Authors, (2026).

Table 3: Levels and factors used in the experiments.

Notations	Factor	Units	Level		
			1	2	3
A	Ti6Al4V	wt. %	5	7	9
B	Compaction pressure	MPa	550	650	750
C	Sintering temperature	°C	1100	1200	1300
D	Sintering time	Min	45	90	135

Source: Authors, (2026).

Table 4: L9 Orthogonal Array.

Exp. no.	A (wt.%)	B (MPa)	C (°C)	D (min)
1	5	550	1100	45
2	5	650	1200	90
3	5	750	1300	135
4	7	550	1200	135
5	7	650	1300	45
6	7	750	1100	90
7	9	550	1300	90
8	9	650	1100	135
9	9	750	1200	45

Source: Authors, (2026).

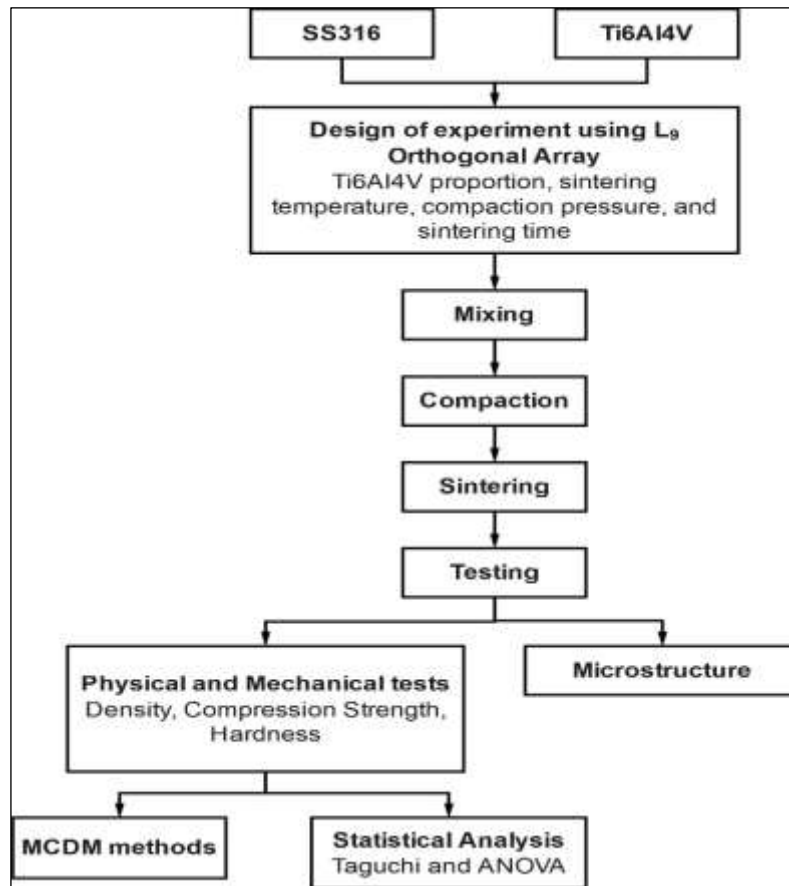


Figure 1: Methodology.

Source: Authors, (2026).

Density was assessed by Archimedes' principle, hardness was determined using Rockwell B tester (Samarth Engineering, 1/16" indenter, 100 kgf load), and compressive strength was quantified utilizing Universal Testing Machine. Nanoindentation demonstrated a substantial enhancement in hardness in all reinforced samples [22]. Microstructural analysis was conducted on the sintered SS316–Ti6Al4V samples to examine particle dispersion and porosity. The specimens were abraded with 400–2000 grit SiC sheets, polished with 1 µm diamond paste, and etched using a modified glyceric acid solution [23]. The etched samples were analyzed with an optical microscope (Metzger-M, India) at different magnifications to evaluate reinforcement distribution and adhesion quality within the matrix. A Taguchi L9 orthogonal array was utilized to examine the effects of Ti6Al4V weight percentages (5, 7, 9%), compaction pressure (650–750 MPa), sintering temperature (1100–1300 °C), and duration (45–135 min). The conclusive factor amounts employed in the trials are delineated in Table 2. Figure 1 shows the methodology used in this research Archimedes' principle (Equation 1) were employed to determine the samples density [24].

$$\rho = (W / (W - W_1)) * \rho_1 \quad (1)$$

where,

q1: Water density

W1: Sample mass at distilled water

W: Sample mass in the air

q: Sample density

II.1 OPTIMIZATION USING SECA – MARCOS TECHNIQUE

II.1.1 Seca

The SCEA approach [25] evaluates multi-objective non-linear technique to concurrently ascertain overall efficiency scores of criteria weights and alternatives for specific decision-making challenge. It were predicated at two reference points. The initial reference point were established using within-criterion variation data, represented by the SD of all criterion, while the subsequent reference point is determined by the correlation measure.

Step 1: Creation of preliminary decision matrix

A decision matrix were constructed based on performance data of m alternatives.

$$X = \begin{bmatrix} x_{11} & x_{12} & \dots & x_{1n} \\ x_{21} & x_{22} & \dots & x_{2n} \\ \dots & \dots & \dots & \dots \\ x_{m1} & x_{m2} & \dots & x_{mn} \end{bmatrix} \quad (2)$$

where x_{ij} signifies the value of the i^{th} alternative on the j^{th} criterion, and $x_{ij} > 0$.

Step 2: Standardization of decision matrix

The components of initial decision matrix were standardized to create the equivalent normalized matrix. Relying on the criterion type, two equations can be utilized. [26].

$$n_{ij} = \frac{x_{ij}}{\max_l x_{lj}} \text{ if } j \in \text{beneficial} \quad (3)$$

$$n_{ij} = \frac{\min_l x_{lj}}{x_{ij}} \text{ if } j \in \text{non - beneficial} \quad (4)$$

n_{ij} , denotes the normalized value within the decision matrix.

Step 3: Computation of the SD and level of discord

The vector for all criterion, $V_j = [n_{ij}]_{m \times 1}$, has now been established. Utilizing the components of between-criteria variation, normalized decision matrix, and within-criterion metrics are assessed as correlation (r_{jl}) and SD (σ_j) for all pair of criterion vectors.

$$\pi_j = \sum_{l=1}^n (1 - r_{jl}) \quad (5)$$

For each criterion in the SECA method, the contrast intensity was determined using the standard deviation, which denotes data dispersion and is represented by σ_b . Conversely, the correlation index, (r_{jl}) signifies the intensity of the linear link among two criteria.

Step 4: Establishment of criteria weights

The reference points for between-criteria and within-criterion mass were derived as values of π_j and σ_j .

$$\sigma_j^N = \frac{\sigma_j}{\sum_{l=1}^n \sigma_l} \quad (6)$$

$$\pi_j^N = \frac{\pi_j}{\sum_{l=1}^n \pi_l} \quad (7)$$

where σ_j^N and π_j^N are the normalized values of σ_j and π_j .

Step 5: Formulation of the multi-objective linear programming model

A multi-objective linear programming model has been formulated, encompassing the following objective functions: minimization of the deviation of criteria and maximization of overall performance (S_i), along with the necessary constraints.

$$\max S_i = \sum_{j=1}^n w_j n_{ij}, \forall i \in 1, 2, \dots, m \quad (8)$$

$$\min \phi_b = \sum_{j=1}^n (w_j - \sigma_j^N)^2, \quad (9)$$

$$\min \phi_c = \sum_{j=1}^n (w_j - \pi_j^N)^2, \quad (10)$$

$$\sum_{j=1}^n w_j = 1, w_j \leq 1, \forall j \in 1, 2, \dots, n \text{ and } w_j \geq \varepsilon, \forall j \in 1, 2, \dots, n \quad (11)$$

Where ϕ_b and ϕ_c represent the changes of criteria weights from the reference points of between-criteria and within-criterion $\varepsilon \leq w_j \leq 1$ delineates the range of w_j and w_j denotes the weight of the j -th criterion, between ε and 1, with ε being the lowest positive value of criterion weight.

Step 6: Enhancement of multi-objective nonlinear programming framework

The previously created optimization model may be transform into a single-objective problem in optimization:

$$\max Z = \phi_a - \beta(\phi_b + \phi_c) \text{ subject to } \phi_a \leq S_i, \forall i \in 1, 2, \dots, m \quad (12)$$

II.1.2 Marcos

The MARCOS method were employed to address many decision-making difficulties due to its straightforward computation. The subsequent steps of the MARCOS technique are as follows [27].

Step 1: Establish a decision-making matrix utilizing Equation 13 The decision matrix $([Z_{ij}]_{p \times q})$ is expanded by adding the Anti ideal value (AIV) and Ideal value (IV)

The AIV and IV were calculated by the equations (13) and (14).

$$AIV = \max(Z_{ij}) \nearrow \text{if } j \in N_{nb}, \text{ and } AIV = \min(Z_{ij}) \nearrow \text{if } j \in N_b \quad (13)$$

$$IV = \max(Z_{ij}) \nearrow \text{if } j \in N_b, \text{ and } IV = \min(Z_{ij}) \nearrow \text{if } j \in N_{nb} \quad (14)$$

Step 2: The revised decision matrix is within range 0 to 1 utilizing the following equation (15).

$$z_{ij} = \frac{Z_{ij}}{Z_{VV}} \nearrow \text{if } j \in N_b \quad (15)$$

$$z_{ij} = \frac{Z_{VV}}{Z_{ij}} \nearrow \text{if } j \in N_{nb} \quad (16)$$

Step 3: The weighted decision matrix were formed using equation (17).

$$\varpi_{ij} = \omega_j \times z_{ij} \quad (17)$$

Step 4 Computing the average of the weighted matrix using the equation (18).

$$k_i = \sum_{j=1}^p \varpi_{ij} \quad (18)$$

Step 5 The degrees for IV and AIV were determined by the following formula.

$$k_i^+ = \frac{k_i}{k_{IV}}, \text{ and } k_i^- = \frac{k_i}{k_{AIV}} \quad (19)$$

Step 6: Regarding AIV and IV, the functions were computed by the following equations.

$$f(k_i^+) = \frac{k_i^-}{k_i^+ + k_i^-}, \text{ and } f(k_i^-) = \frac{k_i^+}{k_i^+ + k_i^-} \quad (20)$$

Step 7: Regarding AIV the and IV, the utility functions were computed [28].

$$f(k_i^+) = \frac{k_i^-}{k_i^+ + k_i^-}, \text{ and } f(k_i^-) = \frac{k_i^+}{k_i^+ + k_i^-} \quad (21)$$

Step 8: The final utility function is determined by

$$f(k_i) = \frac{k_i^+ + k_i^-}{1 + \frac{1-f(k_i^+)}{f(k_i^+)} + \frac{1-f(k_i^-)}{f(k_i^-)}} \quad (22)$$

Step 9: Evaluating the options. The alternatives are graded in descending order of their $f(k_i)$ from best to worst. principles.

III. RESULTS AND DISCUSSION

III.1 TAGUCHI METHOD

This study categorizes physical properties density, under "smaller-the-better" principle of Taguchi technique with the objective of minimizing the weight of the SS316/Ti6Al4V composite. Conversely, hardness and compressive strength fall within the "larger is better" paradigm, aimed at enhancing the strength and hardness of composites.

Consequently, the signal-to-noise ratio was calculated utilizing Equations 3 and 4. Table 5 displays the statistical and experimental outcomes for the hardness, density and compressive strength of SS316/Ti6Al4V composites. ANOVA and Taguchi analysis results was derived with Minitab software [29].

Table 5: Results of statistical analysis for SS316/Ti6Al4V composites' hardness, compressive strength and density.

S.No	Density		Compressive strength		Hardness	
	Result	S/N Ratio	Result	S/N Ratio	Result	S/N Ratio
1	3.032	-9.635	332.34	50.43	39.05	31.83
2	3.058	-9.709	345.56	50.77	39.85	32.01
3	3.096	-9.816	373.86	51.45	42.81	32.63
4	3.037	-9.649	359.47	51.11	42.02	32.47
5	3.058	-9.709	355.36	51.01	42.18	32.50
6	3.103	-9.836	386.29	51.74	43.31	32.73
7	3.064	-9.726	368.52	51.33	41.89	32.44
8	3.075	-9.757	367.80	51.31	42.31	32.53
9	3.111	-9.858	365.19	51.25	43.55	32.78

Source: Authors, (2026).

Smaller- the better:

$$S/N = -10 * \log * \left(\frac{1}{n}\right) \sum_{i=1}^n \left(\frac{1}{y_i^2}\right) \quad (23)$$

larger -the better:

$$S/N = 10 * \log * \left(\frac{1}{n}\right) * \sum_{i=1}^n \left(\frac{1}{y_i^2}\right) \quad (24)$$

When “ y_i ” value for the finding (i) and “n” total number of findings

III.2 COMPOSITES RANKING

III.2.1 Weight Calculation

The powder metallurgy composite has nine possibilities and three criteria, organized in decision matrix presented at table 5, by utilizing Equation (2). Initially, the n_{ij} values were utilized to construct normalized decision matrix according to Eq. (3) & (4). Table 6 displays normalized outcomes.

Table 6: Normalization of decision matrices for SECA analysis.

S.No	Density	Compressive Strength	Hardness
1	1.0000	0.8603	0.8967
2	0.9915	0.8946	0.9150
3	0.9793	0.9678	0.9830
4	0.9984	0.9306	0.9649
5	0.9915	0.9199	0.9685
6	0.9771	1.0000	0.9945
7	0.9896	0.9540	0.9619
8	0.9860	0.9521	0.9715
9	0.9746	0.9454	1.0000

Source: Authors, (2026).

The normalized inside criterion, (σ_j^N), and between criteria, (π_j^N), reference points were used to ascertain the optimal criteria weights through multi-objective linear model. The resultant weights and their deviations from reference points are displayed in Table 5, while overall performance scores (S_i) are also presented. Criteria with elevated normalized reference points were assigned greater weights, hence improving the performance of leading alternatives. The model adeptly balanced the performance enhancement with deviation reduction, ensuring robustness and consistency.

Table 7: Optimized criteria weights and deviation from the reference points.

Criteria	Sigma	Pi	Sigma_N	Pi_N	SECA_Weight
Density	0.0090	3.5477	0.1067	0.4839	0.299
Compressive Strength	0.0411	1.8808	0.4852	0.2566	0.368
Hardness	0.0346	1.9024	0.4081	0.2595	0.333

Source: Authors, (2026).

The criterion weights were calculated as: Density = 0.299, Compressive strength = 0.368, and Hardness = 0.333.

III.2.2 Alternatives evaluation

The choice matrix were constructed after establishing the AIV and IV using Eq. (13) & (14). The decision matrix employed at MARCOS for specified criteria and alternatives were presented in Table 7. According to the MARCOS technique outlined, each value were normalized using Equations (15) & (16). The normalized matrix for MARCOS evaluation were presented at Table 8. Table 8 shows the weighted choice matrix and normalized decision matrix for MARCOS analysis.

Table 8: Weighted and normalized decision matrix for MARCOS analysis.

S.No	Normalization			Weighted Normalization		
	Density	Compressive Strength	Hardness	Density	Compressive Strength	Hardness
1	1.0000	0.8603	0.8967	0.2994	0.3166	0.2983
2	0.9915	0.8946	0.9150	0.2968	0.3292	0.3044
3	0.9793	0.9678	0.9830	0.2932	0.3561	0.3270
4	0.9984	0.9306	0.9649	0.2989	0.3424	0.3210
5	0.9915	0.9199	0.9685	0.2968	0.3385	0.3222
6	0.9771	1.0000	0.9945	0.2925	0.3680	0.3308
7	0.9896	0.9540	0.9619	0.2962	0.3510	0.3200
8	0.9860	0.9521	0.9715	0.2952	0.3504	0.3232
9	0.9746	0.9454	1.0000	0.2918	0.3479	0.3327

Source: Authors, (2026).

Subsequently, Equations (18)-(20) of the MARCOS technique were used to derive the utility functions ($f(k_i^+)$, $f(k_i^-)$) and degree k_i^+ , k_i^- . The utility function, ($f(k_i)$) for all choice were determined by Equation (21). The results of MARCOS were encapsulated at Table 9.

Table 9: MARCOS Results.

S.No	Ki	utility degrees		utility functions		f(ki)	Rank
		Ki+	Ki-	f (ki+)	f (ki-)		
A1	0.9142	0.9222	1.0000	0.5202	0.4798	0.6394	9
A2	0.9304	0.9385	1.0177	0.5202	0.4798	0.6507	8
A3	0.9763	0.9849	1.0679	0.5202	0.4798	0.6828	2
A4	0.9623	0.9707	1.0525	0.5202	0.4798	0.6729	6
A5	0.9575	0.9659	1.0474	0.5202	0.4798	0.6696	7
A6	0.9913	1.0000	1.0843	0.5202	0.4798	0.6933	1
A7	0.9673	0.9757	1.0580	0.5202	0.4798	0.6764	5
A8	0.9687	0.9772	1.0596	0.5202	0.4798	0.6775	4
A9	0.9723	0.9808	1.0635	0.5202	0.4798	0.6800	3
IV	0.9913						
AIV	0.9142						

Source: Authors, (2026).

Ultimately, the alternatives were ranked on the (k_i).. values. Table 9 indicates best processing parameters are 7 wt.% Ti6Al4V reinforcement, a sintering temperature of 1100°C, a sintering duration of 90 minutes and compaction pressure of 750 MPa, GNPs-reinforced Cu/Ti6Al4V composites (0.3 wt% GNPs) were fabricated by vacuum hot pressing, and the influence of sintering settings was examined through orthogonal testing, in contrast to another study. The sintering temperature predominantly affected density, microhardness, and compressive strength, whereas pressure and sintering duration showed negligible contributions. The ideal parameters—1150 °C, 35 MPa, 40 min—produced elevated density (99.34%), microhardness (585.4 HV0.1), and compressive strength (2382 MPa), together with distinct α/β -Ti phases and preserved graphene in the microstructure. [30].

The powder metallurgy composite alternatives organized in descending way as A6, A3, A9, A8, A7, A4, A5, A2, A1. The composite A6, containing 7 wt.% Ti6Al4V, is determined to be the optimal selection for defense and aerospace applications under the specified conditions, based on the nine criteria.

III.3 ASSESSMENT OF THE BEST POSSIBLE MIX OF INPUT PROCESS VARIABLES AND THEIR MAGNITUDES

To determine the optimal levels of factors for density, hardness, and compressive strength, the average utility function value $f(k_i)$ for all level of the factors was assessed using main effect plot of the Taguchi method, with the highest value selected for all factor. The utility function $f(k_i)$ evaluates corresponding values for three tiers of input factors, and principals related to the utility function $f(k_i)$. Table 10 displays the emphasized bold values for utility function $f(k_i)$ representing the maximum values for the three tiers [31].

Table 10: Impact table for utility function $f(k_i)$.

Level	Means				S/N ratio			
	A (wt.%)	B (MPa)	C (°C)	D (min)	A (wt.%)	B (MPa)	C (°C)	D (min)
1	0.6576	0.6629	0.6700	0.6630	-3.644	-3.574	-3.483	-3.573
2	0.6786	0.6659	0.6679	0.6734	-3.369	-3.533	-3.508	-3.437
3	0.6780	0.6853	0.6763	0.6777	-3.376	-3.282	-3.398	-3.379
Delta	0.0210	0.0224	0.0084	0.0147	0.276	0.291	0.110	0.194
Rank	2	1	4	3	2	1	4	3

Source: Authors, (2026).

The ideal parameter combination for the coded level A2B3C3D3 was determined to be 7 wt.% Ti6Al4V (A), 750 MPa compaction pressure (B), 1300°C sintering temperature (C), and 135 minutes sintering time (D), which jointly produced enhanced response characteristics as depicted in Figure 2. A previous study involved the fabrication of graphene-modified TC11 high-temperature titanium alloy utilizing spark plasma sintering under diverse sintering circumstances. Optimal characteristics were attained at 900 °C, 5 minutes and 50 MPa resulting in enhanced compressive strength at both ambient and high temperatures [32].

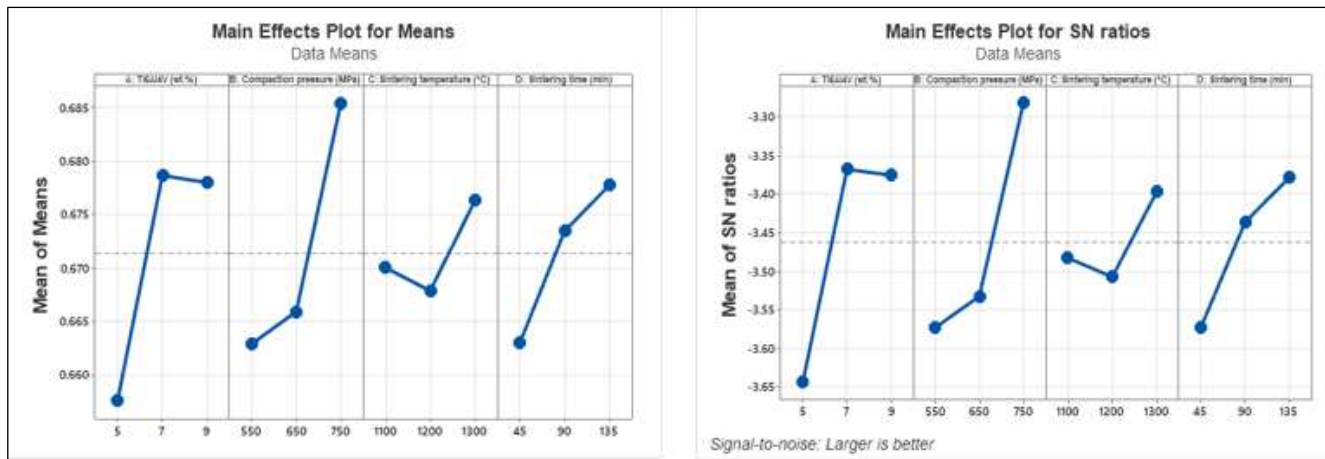


Figure 2: Graph showing a) main effect plot for Mean and b) S/N ratio of utility function $f(k_i)$.

Source: Authors, (2026).

Figure 3 illustrates the microstructural characteristics of SS316/Ti6Al4V composites containing 5wt%, 7wt%, and 9wt% reinforcement, clearly showing how the increasing Ti6Al4V content influences particle dispersion and densification behavior. Figure 3 (a) and (b) 5wt% and 7% Ti6Al4V, the reinforcement particles appear uniformly distributed within the stainless-steel matrix, indicating that the powder blending, compaction, and sintering conditions were effective in promoting homogeneous mixing and strong metallurgical bonding. Figure 3(b) the 7wt% composite, in particular, shows the most refined and continuous microstructure, with smooth matrix regions, clean particle interfaces, and minimal porosity, suggesting enhanced diffusion during sintering and excellent compatibility between the SS316 and Ti6Al4V powders.

Figure 3(c) the reinforcement level increases to 9wt%, the microstructure becomes noticeably less uniform, with evident agglomeration of Ti6Al4V particles and the formation of larger pore pockets. This occurs because the higher volume of hard Ti6Al4V particles reduces the compressibility of the powder mixture, limiting particle rearrangement and densification during compaction and sintering. As a result, localized clusters form and trap pores within the matrix, leading to incomplete bonding and reduced structural integrity. Figure 3 (b) microstructural observations confirm that 7wt% Ti6Al4V provides the most balanced distribution and densification, while higher reinforcement levels introduce manufacturing challenges that negatively affect the final mechanical properties.

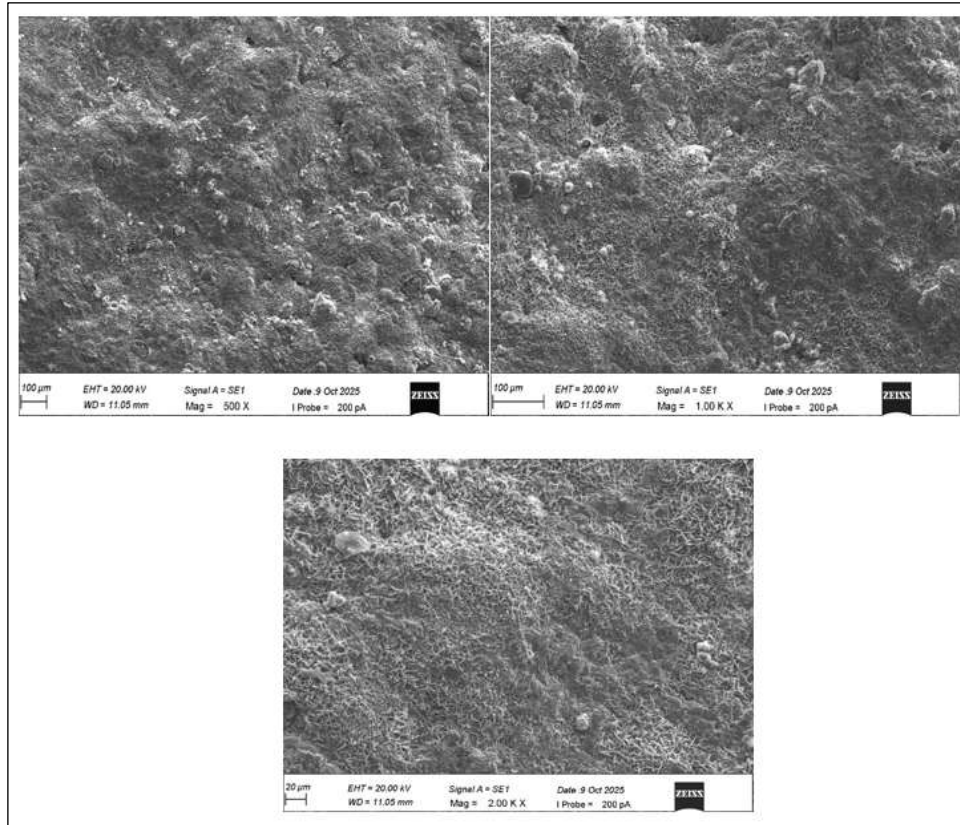


Figure 3: Microstructure of (a) SS316 /5% Ti6Al4V, (b) SS316/7% Ti6Al4V, and (c) SS316/9%Ti6Al4V composites.
Source: Authors, (2026).

III.4 UTILIZING ANOVA TO EXAMINE HOW INPUT PROCESS VARIABLES IMPACT PERFORMANCE METRICS

ANOVA was conducted to assess the contribution and importance of all process element to utility function (ki) value. Table 11 presents the ANOVA analysis, illustrating the F-ratio contribution of all process element to the density, compressive strength and hardness. ANOVA table reveals that, the process factors Ti6Al4V (wt.%) and compaction pressure (MPa) contribute 38.85% and 40.28%, respectively, making them the most significant factors. They are followed by sintering time (min) with a contribution of 15.66% and sintering temperature ($^{\circ}\text{C}$) with 5.21% contribution to the process.

Regression Eq (25) for the established mathematical model were presented below. [33].

$$\begin{aligned} \text{Utility Function (f(ki))} = & 0.6714 - 0.01379 A \text{ (wt.\%)}_5 + 0.007226 A \text{ (wt.\%)}_7 + 0.006568 A \text{ (wt.\%)}_9 - 0.008473 \\ & B \text{ (MPa)}_{550} - 0.005471 B \text{ (MPa)}_{650} + 0.01394 B \text{ (MPa)}_{750} - 0.001361 C \text{ (}^{\circ}\text{C)}_{1100} - 0.003533 C \text{ (}^{\circ}\text{C)}_{1200} + 0.004894 \\ & C \text{ (}^{\circ}\text{C)}_{1300} - 0.008405 D \text{ (min)}_{45} + 0.002065 D \text{ (min)}_{90} + 0.006341 D \text{ (min)}_{135} \end{aligned} \quad (25)$$

III.5 COMPARISON OF DECISION MAKING TECHNIQUE

Comparisons were conducted utilizing ARAS, WASPAS, MOORA, and COPRAS methodologies. The selected approaches utilize the identical weights derived from SECA method, as applied at MARCOS ranking, to guarantee just and impartial comparison. Table 11 displays the alternative composites produced through various methods.

Table 11: Composite ranking employing several techniques for decision-making.

S.No		MARCOS		ARAS		WASPAS		MOORA		COPRAS
	f(ki)	Rank	Ki	Rank	Qi	Rank	Yi	Rank	Ui	Rank
A1	0.6394	9	0.9131	9	0.9133	9	0.1342	9	92.084	9
A2	0.6507	8	0.9296	8	0.9300	8	0.1408	8	93.751	8
A3	0.6828	2	0.9762	2	0.9763	2	0.1592	2	98.456	2
A4	0.6729	6	0.9617	6	0.9621	6	0.1535	6	96.990	6
A5	0.6696	7	0.9569	7	0.9573	7	0.1516	7	96.507	7
A6	0.6933	1	0.9915	1	0.9913	1	0.1653	1	100.000	1
A7	0.6764	5	0.9670	5	0.9672	5	0.1556	5	97.523	5
A8	0.6775	4	0.9685	4	0.9687	4	0.1562	4	97.671	4
A9	0.6800	3	0.9720	3	0.9722	3	0.1576	3	98.033	3

Source: Authors, (2026).

Alternative A6 were consistently regarded as first option, while alternative A3 were uniformly positioned as secondary choice across decision-making processes employed. Table 11 demonstrated that a ranking analogous to MARCOS was achieved for WASPAS, ARAS, MOORA, and COPRAS. Furthermore, the statistical method referred as Spearman's correlation analysis were employed to assess link among rankings obtained by SECA-MARCOS. The rank correlation among two datasets were calculated by Equation (26).

$$RC = \frac{(p^3 - p) - 6 \sum_{i=1}^p \delta_i^2}{p^3 - p}, \nearrow -1 \leq RC \leq +1 \quad (26)$$

The correlation coefficient of 1 were attained among ranking of MARCOS method and COPRAS, WASPAS, MOORA, and ARAS methodologies. The strong correlation among ranks illustrates the stability and robustness of the integrated SECA-MARCOS methodology. The proposed method can facilitate informed and logical decision-making at selection and assessment of powder metallurgy composite materials.

IV. CONCLUSIONS

Stainless steel SS316/Ti6Al4V composites were effectively produced by the powder metallurgy (PM) method. MARCOS utilized Taguchi-based optimization and ANOVA to evaluate the effect of four powder metallurgy factors: SiC (wt.%), compaction pressure (MPa), sintering temperature (°C), and sintering time (min). The physical and mechanical properties, including density, hardness, and compressive strength, were utilized as assessment criteria. The SECA method were employed to assign mass to the selected criteria, while MARCOS approach were utilized to determine the composites rank. The subsequent conclusions were derived from the statistical analysis: The ideal processing parameters were determined to be 7 wt.% Ti6Al4V reinforcement, a sintering temperature of 1100°C, a sintering duration of 90 minutes and compaction pressure of 750 MPa. The results SECA-MARCOS approach demonstrate that the composite with 7 wt.% Ti6Al4V is the most advantageous for defense and aerospace applications.

The utility functions $f(ki)$ – Taguchi analysis identified the optimal combination of process variables to attain favorable material properties, yielding minimum density and maximum compressive strength and hardness at 7 wt.% Ti6Al4V (A), 750 MPa compaction pressure (B), 1300°C sintering temperature (C), and 135 minutes sintering duration (D). The combined effects of density, hardness and compressive strength demonstrated that Ti6Al4V (wt.%) accounted for 38.85%, compaction pressure (MPa) for 40.28%, sintering temperature (°C) for 15.66%, and sintering time (min) for 5.21% of the total variability, signifying that these variables exerted a substantial influence on the mechanical and physical characteristics of the composites. Moreover, congruent rankings was attained for specified alternatives and criteria employing the ARAS, WASPAS, MOORA, and COPRAS techniques. The Spearman's correlation among suggested technique and other MCDM methodology illustrate consistency of the ranking findings. The study presented a thorough SECA-MARCOS method to tackle the issue of material selection.

V. AUTHOR'S CONTRIBUTION

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Supervision: Bubesh Kumar D and Sangeetha Krishnamoorthi S.

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