



Numerical Modelling and Optimization of the Surface Qualities of Laser Cladded Ti-6Al-4V Alloy

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Abstract

Ti6Al4V alloy is one of the most widely utilized engineering metals, but it has a reduced hardness for high-temperature abrasive applications. In order to modify the surface of a Ti6Al4V alloy plate, a Cobalt-Nickel (Co-Ni) powder combination with increased hardness and corrosion resistance was used during the laser cladding process. For optimal efficiency, the Co proportion of the powder was modified between 30, 50, and 70 wt% respectively. The scan speed and laser power of the operation process were modified between 0.6, 0.9, and 1.2 m/s and 700, 800, and 900 W respectively. The response properties examined include; microhardness of the coating, surface roughness, and clad depth. Response surface methodology was utilized in the experimental design, response property modeling, and process optimization respectively. The statistical analysis revealed that the input variables had significant effects on the response properties and that the trend of the responses depended on the interaction pattern between the input variables. The developed numerical models were validated for property prediction. It was noted that the optimization procedure and confirmation experiments produced response properties with marginal error. The optimal input combination for producing the balanced performance of the Co-Ni coating on the Ti6Al4V alloy substrate yielded 70wt.% Co proportion, 0.86 m/s scan speed, and 900 W laser power respectively.

Keywords Cobalt-Nickel coatings · Laser cladding · Numerical models · Optimization · Ti6Al4V surface treatment

Introduction

Ti6Al4V is a titanium alloy that has gained popularity in aerospace, industrial, marine, and medicinal engineering applications. High strength-to-weight ratio, high corrosion resistance, and biocompatibility are inherent properties. For

Extended author information available on the last page of the article

high-performance abrasive applications, the surface hardness of the alloy is inadequate. Coating a surface with a denser and harder material is one method to modify it [1, 2]. Laser cladding is a commonly accepted surface treatment technique for metals. According to the laser theory, a photon with energy equal to the difference between the excited and ground states of an atom collides with an excited atom, and another photon with the same energy is thereby released [3]. The scope of laser research has been gradually expanded. Different types of advancements in laser structure and design increased the lifetime of the lasers, including concentrated beam width, improved output continuity, and controlled and brief pulse duration [4]. The importance given to laser technology was influenced by several factors, including rising telephone use, electronic transmission, television signal relay, and the requirement for space communication [5]. The link between power and temperature is one of the key reasons lasers are far more useful in space than in the atmosphere [6]. The link between power and temperature shows that the chaotic electron motions interfere with the electrical flow, hence, laser materials have stronger conductivity in cold environments and less in hot conditions [7].

The method of laser cladding involves fusing a different metal to a substrate surface with the least amount of substrate melting possible [8]. The technological potential of the process, as well as its productivity and coating quality, can all be considerably increased by using focused laser radiation to coat metals, compared to conventional powder-cladding techniques. A reduction in the substrate material and clad layer mixing zone has the effect of reducing the thickness of the applied intermediate layer and the complexity of the cladding process, as well as an increase in overall operation productivity. This can lead to enhancing the processability, effectiveness, and adhesion resistance of the material that has been applied to the substrate while lowering the porosity and the quantity of non-metallic inclusions that are typical of processing techniques that use fluxes [9, 10].

Chen et al. reported on laser cladding of Ni-Ti-coated Ti6Al4V alloy surfaces. The result indicated that scanning speed enhanced hardness performance [11]. In the investigation conducted by Song and his colleagues [12], titanium plates were laser-clad with Ti6Al4V. Variations in scanning speeds such as 300, 400, 500, and 600 mm/min were utilized. It was observed that as scanning speed increased, hardness increased, resulting in enhanced wear resistance. Using the same method, Ti6Al4V alloy plate was coated with WC-Ni powder composite [13]. With a rise in specific heat input, the thickness of the cladding increased, thereby enhancing the substrate's hardness. Other notable findings of laser cladding investigations as additive manufacturing processes are documented in the references [14–16].

However, these documented findings only reported the properties of coatings by varying a single experimental variable. Multiple input parameters are utilized in additive processing, and these parameters can be adjusted to achieve optimal and balanced performance. The energy intensities have a significant impact on the quality of the coating. The energy intensity is determined by laser power (P), scan speed (v), hatch distance (h), and layer thickness (l) [17]. Optimization of these parameters is essential for attaining optimal performance of laser-cladded coatings. This study examines the effect of varying laser power and scan speed at constant hatch distance and layer thickness. The laser intensity varies between 700, 800, and 900 W, while

the scan speed varies between 0.6, 0.9, and 1.2 m per second. The cladding comprises cobalt-nickel particles with variable cobalt proportions of 30, 50, and 70%. To improve the surface properties of Ti6Al4V alloy, the powder composition was chosen based on its high-temperature strength, hardness, and corrosion resistance [18]. In the present investigation, there are three input variables: laser power, scan speed, and cobalt proportion. The conventional experimental procedure requires 81 experimental trials, which is energy- and cost-intensive. Similar to Chowdhury et al. [19], the response surface method was incorporated into the experimental design, modeling, and optimization of the results to reduce labor and cost while still achieving the same experimental objective and optimization. In addition, there are few studies designed to model and optimize laser cladding of Ti6Al4V alloy, which is the gap the current study intends to fill. Therefore, this study aims to optimize the experimental process and modeling of the response properties of Co-Ni coatings on Ti6Al4V alloy.

Experimental Procedure

The procedure entailed the experimental design adopting Box Behnken design approach and statistical analysis of experimental results. Prior to the experimental protocol, preliminary experiments were carried out in triplicates for the input variables to explore the viability of this study.

Box-Behnken Design (BBD)

Cobalt (Co) proportion (A), scan speed (B), and laser intensity (C) were the three independent variables used in the BBD experimental design following standard protocols [18]. Through surface plots, the interaction between the three experimental variables was investigated using statistical processing and the response surface method. Also investigated were the significance of each experimental variable and their interaction, as well as the impact of the interaction on the trend of the responses. Included in the investigations are microhardness, surface roughness, and clad depth. Following our previous works, numerical models were developed for the responses as a function of the experimental variables, and the optimal combination of the three variables for the coating's optimal performance was determined through an optimization procedure [19, 20]. These were accomplished with Design Expert 13 software. Table 1 displays the levels of the input variables utilized in this study, while Table 2 displays the parametric combination derived for each experimental trial.

Table 1 Level of the input variables

Input variables	Minimum level	Medium level	Maximum level
Cobalt (Co) proportion (wt%)	30	50	70
Scan speed (m/s)	0.6	0.9	1.2
Laser power (W)	700	800	900

Materials and Methods

The investigation was conducted using a 40 mm x 20 mm x 20 mm titanium Ti6Al4V plate substrate. Alcohol was used to sanitize the surface after it was sand-blasted to remove surface impurities and affixed oxides. For the coating, a Cobalt-Nickel (Co-Ni) power blend was utilized. According to Table 2, the Co and Ni powder were mixed in proportions of 30, 50, and 70wt.% Co. The surface of the titanium alloy was cladded using a laser deposition machine (Nd-YAG) with a focal length of 195 mm and a beam diameter of 3 mm. Co proportion, scan speed, and laser power were varied as shown in Table 2, whereas powder flow rate, scan time, and hatch distance were held constant at 5 g/s, 15 min, and 0.3 mm, respectively. The procedure was carried out in an argon atmosphere with a flow rate of 2 l/min. Nine samples were produced for each run order (Table 2), of which three were evaluated for microhardness, three for surface irregularity, and three for cladding depth. As per each run, the average of the three results was recorded for each property.

Results and Analysis

Actual and Predicted Outcomes

The variations in the actual and predicted values of the properties under investigation are presented in Table 3.

The measured and predicted properties for the examined properties are showcased in Table 3. The percentage difference between the predicted and the actual experimental outcome is less than 5%, acceptable for response modeling.

Table 2 Input variable combination

Runs order	Co proportion (wt%)	Scan speed (m/s)	Laser power (W)
1	30	1.2	800
2	70	1.2	800
3	50	1.2	900
4	30	0.9	700
5	30	0.6	800
6	70	0.6	800
7	70	0.9	900
8	70	0.9	700
9	30	0.9	900
10	50	0.9	800
11	50	1.2	700
12	50	0.6	900
13	50	0.6	700

Table 3 Actual and predicted values for the examined properties

Runs	Microhardness (HV)		Surface roughness (μm)		Clad depth (mm)	
	Actual Value	Predicted Value	Actual Value	Predicted Value	Actual Value	Predicted Value
1	514.00	511.75	5.50	5.40	0.8500	0.8600
2	702.00	707.25	6.30	6.28	0.9300	0.9325
3	644.00	639.50	7.00	7.11	0.9500	0.9463
4	536.00	536.75	5.10	5.19	0.8300	0.8288
5	477.00	471.75	3.80	3.83	0.7400	0.7375
6	665.00	667.25	4.80	4.90	0.8700	0.8600
7	786.00	785.25	5.20	5.11	1.33	1.33
8	726.00	719.25	6.20	6.21	0.9300	0.9363
9	570.00	576.75	4.20	4.19	1.25	1.24
10	636.00	636.00	6.40	6.40	0.9500	0.9500
11	586.00	587.50	8.00	8.01	0.5500	0.5413
12	602.00	600.50	5.50	5.49	0.8400	0.8488
13	542.00	546.50	6.80	6.69	0.4400	0.4438

Variance Analysis

Previous research employed variance analysis to determine the significance of the input variables on the responses at a confidence level of 95% using p -value as the functional term [21, 22]. If the p -value of the input terms or interaction terms is less than 0.05, the term is deemed significant; if it is greater than 0.05, the term's influence on the response is deemed insignificant. As shown in Table 4, the p -values for the input variables A, B, and C are less than 0.05, indicating that the input variables had a significant effect on the outcomes. In the case of cross-interactions AB, AC, and BC, the p -values are less than 0.05, as all responses are affected [23]. In this instance, the cross-interaction exhibited insignificant effect

Table 4 shows the variations in the analysis of variance

Source	Microhardness	Surface roughness	Clad depth
A-Co proportion	<0.0001	0.0024	0.0016
B-Laser speed	0.0063	0.0007	0.0016
C-Laser power	0.0028	0.0020	<0.0001
AB	1.0000	0.5382	0.1411
AC	0.2117	0.7519	0.4848
BC	0.9108	0.3751	1.0000
A ²	0.2744	0.0006	0.0004
B ²	0.0022	0.1642	<0.0001
C ²	0.1302	0.0791	0.3703
Model	0.0007	0.0018	0.0001

on the responses. While square interaction A^2 had a substantial effect on surface roughness and clad depth, its effect on microhardness was negligible. B^2 contributes significantly to microhardness and clad depth, whereas its contribution to surface roughness is negligible. Regarding square interaction C^2 , the p -values for all response properties are larger than 0.05, implying an insignificant effect on the responses. The analysis demonstrated that the trend of the response properties depends more on the magnitude of the input variables than on their interaction terms.

The p -values for the models of the responses are evaluated to be greater than 0.05, as shown in Table 4. It indicates that there is a strong relationship between the obtained experimental data and the models.

Numerical Models

The numerical models for the response properties are showcased in Eqs. 1, 2, and 3 respectively.

$$ccMH = 519.1875 + 0.4750 A + 1155.0000 B - 1.6825 C - 0.0000 AB + 0.0033 AC - 0.0167 BC + 0.0181 A^2 - 597.2222 B^2 + 0.0011 C^2 \quad R^2 = 98.79 \quad (1)$$

$$ccSR = 16.4500 + 0.4106 A - 2.6250 B - 0.0469 C - 0.0083 AB - 0.0000 AC + 0.0025 BC - 0.0037 A^2 + 1.9444 B^2 + 0.0000 C^2 \quad R^2 = 98.62 \quad (2)$$

$$ccCD = -3.0097 - 0.0296 A + 5.1917 B + 0.0036 C - 0.0021 AB - 0.0000 AC + 0.0000 BC + 0.0004 A^2 - 2.7361 B^2 - 0.0000 C^2 \quad R^2 = 97.82 \quad (3)$$

MH, SR, and CD are microhardness (HV), surface roughness (μm), and clad depth (mm) accordingly. A, B, and C are Co proportion, scanning speed, and laser power respectively.

The coefficient of determination (R^2) for the models is greater than 95%, indicating that the models exhibit excellent accord with the data, with less than 5% variance. The positive terms in the model represent terms that have a positive effect on the responses, and they are regarded as the model's positive terms. The negative terms, on the other hand, highlight those with a negative effect on the response and the model [24].

Probability Plots

The probability plot is a proof and confirmation of the degree of fitness between the data and the models. As seen in Fig. 1a, b, and c, the experimental data are plotted along the mean line from minimum to maximum, indicating that the data and model are in good agreement. On this basis, it is assumed that the models (Eqs. 1, 2, and 3) statistically represent the data as presented in references [25].

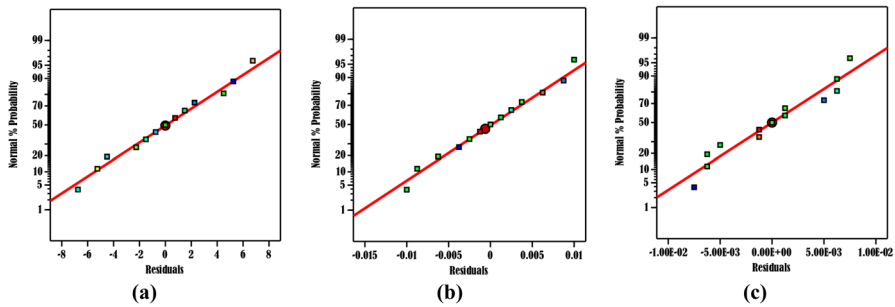


Fig. 1 Normal probability plot for response properties (a) microhardness (b) surface roughness (c) clad depth

Response Surface Plots

The trend of the property responses as a function of the input variables is depicted by the surface plots. Similar to the literature, [26] surface plots have been utilized to examine the effects of the interactive patterns between the variables and how they influence the response [26].

Microhardness

Figure 2 depicts the trend of microhardness as a function of the interaction between (a) Co proportion and scanning speed at a constant laser power of 800 W, (b) Co proportion and laser power at a constant scanning speed of 0.9 m/s, and (c) scanning speed and laser power at 50% Co proportion. In Fig. 2a, coating deposition at Co proportions between 30 and 70% at scanning speeds between 0.6 and 0.9 m/s is synergistic with microhardness, resulting in a value increase. Similarly, Co dosage at scanning speeds between 0.9 and 1.2 m/s led to a decrease in hardness. In Fig. 2b, microhardness is enhanced when the Co proportion is between 30 and 70% and the laser power range from 700 to 900 W. Figure 2c shows that scanning speeds of

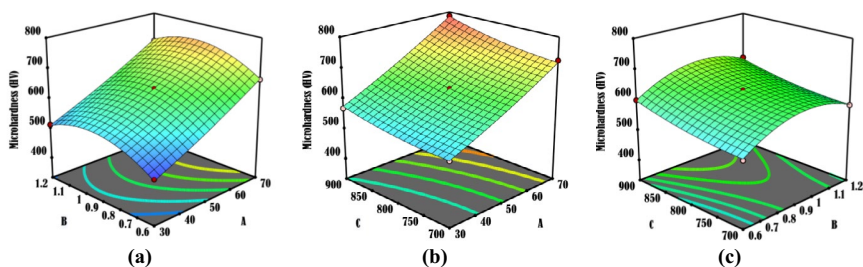


Fig. 2 Variation of microhardness as a function of the interaction between (a) Co proportion and scanning speed at constant laser power of 800 W (b) Co proportion and laser power when holding scanning speed at 0.9 m/s and (c) scanning speed and laser power at Co constant proportion of 50%. A stand for Co proportion (%), B for scanning speed (m/s), and C for laser power (Watts)

0.6–0.9 m/s at a laser power of 700–900 watts improved microhardness, whereas the same range of laser power at scanning speeds of 0.9–1.2 m/s degrades hardness [26].

Surface Roughness

Figure 3 depicts the surface plot for surface roughness as a function of the interaction between (a) Co proportion and scanning speed at a constant laser power of 800 W, (b) Co proportion and laser power at a constant scanning speed of 0.9 m/s, and (c) scanning speed and laser power at 50% Co proportion. As observed in Fig. 3a, laser cladding with a Co proportion of the coating between 30 and 70 wt% at a scanning speed of 0.6–0.9 m/s caused an increase in the surface roughness of the material. Also, laser cladding with the same Co proportion applied to the surface at a scanning speed of 0.9–1.2 m/s caused an increase in surface roughness (Fig. 3b). Figure 3c illustrates that as scanning speed increases from 0.6 to 12 m/s at laser powers between 700 and 900 W, surface roughness increases linearly.

Clad Depth

Figure 4 depicts the surface plot for surface roughness at the interaction of (a) Co proportion and scanning speed at a constant laser power of 800 W, (b) Co proportion and laser power at a constant scanning speed of 0.9 m/s, and (c) scanning speed and laser power at 50% Co proportion. In Fig. 4a, the clad depth decreased between 30 and 50% Co, whereas the depth increased between 50 and 70% Co. Additionally, 0.6–0.9 m/s scanning speed was advantageous for clad depth, whereas 0.9–1.2 m/s is deleterious. As shown in Figs. 4b and 30–50% Co proportion at 700–900 W laser power increases clad depth, whereas 50–70% Co proportion at the same range of laser power caused clad depth to decrease. In addition, Fig. 4c demonstrates that 0.6–0.9 m/s scanning speed at 700–900 W laser power is favorable for clad depth, whereas 0.9–1.2 m/s scanning speed at 700–900 W reduces clad depth.

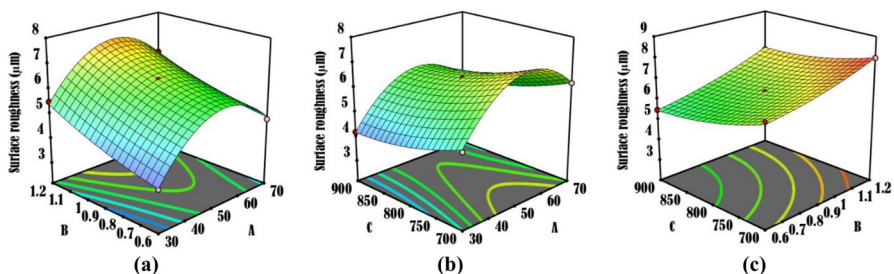


Fig. 3 Variation of surface roughness as a function of the interaction between (a) Co proportion and scanning speed at constant laser power of 800 W (b) Co proportion and laser power when holding scanning speed at 0.9 m/s and (c) scanning speed and laser power at Co fixed proportion of 50%. A stand for Co proportion (%), B for scanning speed (m/s), and C for laser power (Watts)

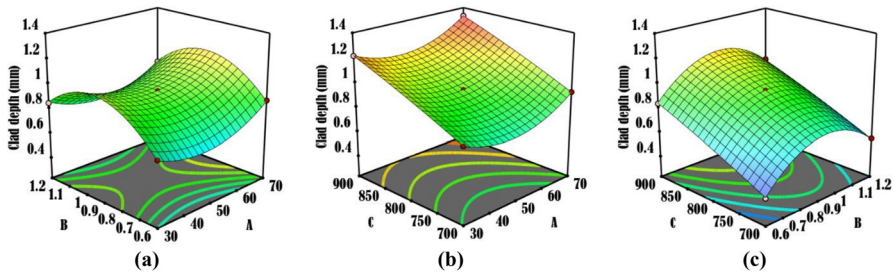


Fig. 4 Variation of surface roughness as a function of the interaction between (a) Co proportion and scanning speed at constant laser power of 800 W (b) Co proportion and laser power when holding scanning speed at 0.9 m/s and (c) scanning speed and laser power at Co proportion of 50%. A stand for Co proportion (%), B for scanning speed (m/s), C for laser power (Watts)

Optimization

According to previous research [23, 27], the response surface method is a reliable technique for determining the optimal combination of input parameters for achieving a balanced combined response. Using Design Expert 13 software, simultaneous optimization was performed on the three responses from the results obtained [28–30]. Table 5 shows the conditions governing the optimization procedure.

The optimal conditions predicted based on the optimization results shown in Fig. 5 are 70% Co proportion, 0.8559 m/s scanning speed, and 900 W laser power. The predicted response value for microhardness showed 781.23 HV, surface roughness had 5.00436 μm , and 1.32071 mm clad depth. However, the microhardness, surface roughness, and clad depth validation results were 779 HV, 5.22 μm , and 1.29 mm for the confirmation experiment conducted in the laboratory. The deviation between the predicted optimal value for the response properties and the confirmation result is negligible (less than 5%), validating the model for response prediction further [22]. In this case, the predicted optimal condition is capable of producing a coating with balanced performance.

Table 5 Conditions for the optimization procedure

Name	Goal	Lower limit	Upper limit
A-Co proportion	is in range	30	70
B-Laser speed	is in range	0.6	1.2
C-Laser power	is in range	700	900
Microhardness	maximize	477	786
Surface roughness	minimize	3.8	8
Clad depth	maximize	0.44	1.33

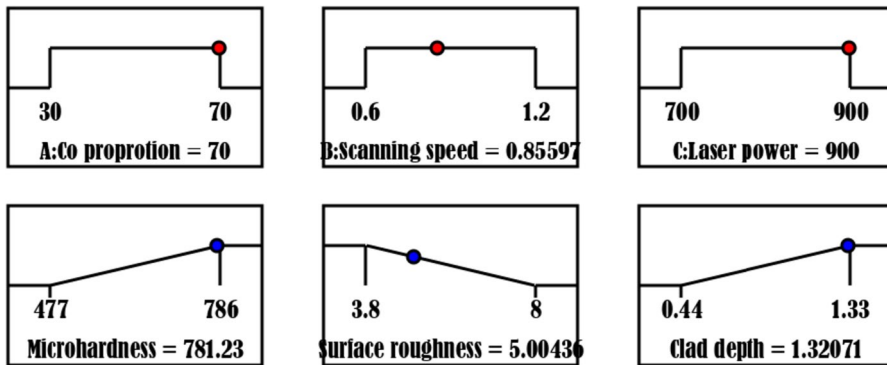


Fig. 5 Optimization ramp

Conclusion

The focus of the investigation was the modeling and optimization of the laser cladding process used to coat Ti6Al4V substrates with Cobalt-Nickel (Co-Ni) powder. Co proportion (30, 50, and 70 wt%), scan speed (0.6, 0.9, 1.2 m/s), and laser power (700, 800, and 900 W) are input variables. The following culminated at:

- i. The variance analysis revealed that the input variables substantially influenced the responses' trend. The cross-interactions between the input variables had no effect on the responses, whereas the square interactions between the individual variables had a significant effect on the responses.
- ii. The numerical models developed demonstrated that the models are significant and exhibit a high degree of fitness with the data, and the normal probability plot provides additional confirmation of the data.
- iii. The surface plots illustrated that the responses are dependent on the interaction pattern between the input variables.
- iv. The optimization tool predicted 70wt.% for Co proportion, 0.8559 m/s for scan speed, and 900 W for laser power as a consequence of the optimization procedure. The predicted response properties for microhardness, surface roughness, and clad depth are 781.23 HV, 5.00436 m, and 1.32071 mm, respectively. The confirmation experiment conducted at 70wt.% Co proportion, 0.86 m/s scan speed, and 900 W laser power produced respective values of 779 HV, 5.22 μm , and 1.25 mm. Since the difference between the predicted and confirmed results is minimal, the models are certified for future response prediction.
- v. Therefore, it is concluded that the optimal proportion of 70wt.% Co, 0.86 m/s scan speed, and 900 W laser power produced coatings with balanced performance.

Author Contributions This work was carried out in collaboration between all authors. Authors: Olanrewaju Seun Adesina, Abayomi Adewale Akinwande, Adeolu Adesoji Adediran, designed the study, performed the experiment, interpreted results and wrote the first draft of the manuscript. Authors, Olanrewaju Seun Adesina, Olufemi Oluseun Sanyaolu, Modupe Eunice Sanyaolu managed the analyses of the study, managed literature searches and graphical editing. All authors read and approved the final manuscript.

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

Declarations

Ethical Approval Collection of plant material, comply with relevant institutional, national, and international guidelines and legislation.

Consent to Participate Not applicable.

Consent for Publication Not applicable.

Competing Interests The authors declare no competing interests.

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