Evaluating the impacts of laser process parameters on microstructure and microhardness of H13-TiC composite using the mathematical modelling

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Abstract

To achieve an optimum microstructure and hardness of the H13-TiC composite, we aim to optimize and improve the laser process parameters of the composite. In the beginning, TiC particles due to important properties such as high hardness, high modulus, low density and high thermal stability were successfully deposited on the H13 hot work tool steel using a pulse Nd: YAG laser. In the deposition process, laser scanning speeds of 2, 7 and 12 mm/s, pulse widths of 6, 8 and 10 ms and operational distances of 4, 5 and 6 mm were used. Then, the response surface methodology was used to find the relationships between three independent variables, develop a mathematical model, better understand the simultaneous effects of variables on the properties of composite area and achieve the optimal values of these variables. XRD and EDS were used to identify the phases, and FESEM and SEM were applied to evaluate the microstructure. The obtained results demonstrate that optimal conditions for the desirable microstructure on the composite surface are achieved at the scanning speed, pulse width and operational distance of 12 mm/s, 9.96 ms and 5.94 mm, respectively. Therefore, using this condition, the microhardness of 1606.49 Vickers is obtained.

Keywords H13-TiC composite · Response surface method (RSM) · Scanning speed · Pulse width · Operational distance · Microstructure

1 Introduction

Over the last few decades, due to its remarkable hot strength and astounding toughness, steel H13 has been used in various industries, including extruding tools, hot-forging and casting dies [1–3]. Such tools must be resistant at the heavy loads, without failure and without excessive deformation and wear. One solution to solve these problems is to incorporate second-phase particles into the steel matrix. For this purpose, a new class of materials called

metal matrix composites has emerged which signify notable wear and erosion resistances, higher hardness and stiffness at a lower density in comparison to the matrix. Existence of ceramic particles leads to a decrease in the matrix ductility and improves anisotropy in properties [4–6]. It has been reported that the addition of the thermodynamically stable TiC particles into a hard martensitic matrix leads to a meaningful increase in features like hardness, stiffness and wear resistance [7]. The need for improving the performance and extending the service life of the components

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subject to wear, erosion, corrosion and high temperature oxidation has led to the emergence of different techniques such as thermal spraying [8, 9], plasma spraying [10] and common arc welding [11] for material correction in recent decades [12, 13]. Among these methods, laser surface modification is widespread today and has the least impact on the mechanical attributes of the substrate. This is due to its unique properties like the creation of a suitable metallurgical bond among the coating and substrate, high power density, high cooling and heating rates, minimal distortion and heat affected area, as well as gradual change of properties such as hardness is widespread today and has the least impact on the mechanical attributes of the substrate. Otherwise speaking, achieving the appropriate microstructure with gradual changes in the properties from the surface to the substrate led to a reduced thermal stress caused by the discrepancy in the thermal expansion coefficient among the coating and the substrate [14–20]. Furthermore, meaningful grain modification and homogeneous microstructures with small dendrites in the surface layer can be attained [21].

The prominent features of the laser heating process can be noted features like: (i) having a narrow beam focusing zone, (ii) having a very low heat input that in turn generates a very narrow heat affected zone (HAZ), (iii) having less residual stress, (iv) having less deformation without additional pre-and post-weld thermal treatments [22]. In addition, it benefits from other features such as (a) the ability to precisely control the depth and width of processing, (b) capability to selectively process-specific areas of a piece and (c) ability to process complex parts. Therefore, it can minimize microstructural changes in the base metal that lower the mechanical strength and chemical resistance [23].

The surface laser modification process is performed in two stages: single and two steps. In the single-step method, the material is applied to the melt pool as powder or wire simultaneously with the surface scanning by the laser beam. In the two-step method, the desired powder composition with organic paste is placed on the subsurface and then subjected to laser beam scanning [24, 25]. The general theory of the two-step method is stated by Powell and his colleagues [26].

The major advantage of this method is the increased laser absorption due to the reduction of the reflectance of the surface from the high reflectance alloys, especially for small and complex pieces [27].

The surface laser modification process is influenced by various factors for example laser power, laser beam scanning speed, laser beam energy, laser beam diameter and pulse width, focal length of laser beam to substrate and type and amount of protective gas. Providing a complete description of this process is complicated because factors

such as convection, infiltration, cooling rate during freezing and solid transformations and laser radiation interference with pre-applied coating are involved. A significant amount of work has been done on the influence of laser surface modification process parameters.

For example, Kadolkar and et al. [28], have investigated the microstructural and dimensional changes of the composite coating due to the energy density change in the laser modification surface of aluminum alloys. The obtained results of this work specify that the energy transfer to the substrate is reduced by increasing the surface scanning speed by laser beam and consequently the area affected by the laser is reduced and if the scanning speed is increased the coating will not reach a defined level.

In investigation of the impact of the laser process parameters on extruded mold, Capello et al. [29], stated that as the pulse width increased, the energy input to the substrate increased, resulting in a broadening of the coating profile; they expressed the pulse width as the most important parameter affecting the process.

In order to increase abrasion resistance coating using laser cladding Kong, et al. [30], studied the microstructure and properties of TiC-H13 composite. They Proved that TiC particles as the reinforcing phase uniformly dispersed within the coating.

Yan, et al. [31], examined the effect of TiC particles on tempering (600 °C) resistance of composite coating by semiconductor the laser cladding. The obtained results signify that with increasing TiC content, the microhardness of cladding layer increased significantly, while maintaining high hardness after tempering.

However, according to the literature review related to this field, no modelling reports are found which determine the optimal amount of variables associated with the laser process. On the basis of information gathered, in recent years although a large number of variables are likely to contribute in coating properties of H13-TiC composite, in this work, the significant parameters including scanning speed, pulse width and operational distance variables were used to develop mathematical model using response surface methodology (RSM). As a result, the current work aims to optimize and improve the laser process parameters to acquire the optimal microstructure and hardness of the H13-TiC composite. By finding quantitative mutual relationships among scanning speed, pulse width and operational distance, RSM facilitates development of the mathematical model which offer systematic data and predict the model at the experimental range. Additionally, so far, few studies have reported the relationships between laser process parameters and their effects on microstructure of the H13-TiC composite, which is discussed in this article.

Table 1 The H13 hot work tool steel's chemical composition

Element	Fe	Cr	Si	Mn	Mo	S	V	P	C
Wt%	Balance	4.75–5.5	0.8–1.2	0.2–0.5	1.1–1.75	0.03	0.8–1.2	0.03	0.35–0.45

Fig. 1 A demonstration of laser surface modification process using pulse laser, schematically**Table 2** Operational parameters of pulse Nd:YAG laser

Laser process parameters	Condition	Unit
Wave length	1.064	μ
layer thickness	200	(μm)
Pulse frequency	15	Hz
Pulse width	6,8,10	ms
Operational distance	4,5,6	mm
Scanning speed of laser	2,8,12	mm/s

XPert Pro model X-ray diffractometer. The hardness of the composited area is signified with a Vickers microhardness tester (Buehler) at a load of 30 g for 15 s.

2 Experimental procedure

2.1 Materials and methods

In the current study, H13 tool steel discs with a dimensions of 50×5 mm, are considered as a substrate, with the chemical composition of this alloy given in Table 1. A pulsed Nd:YAG laser equipped with the highest pulse frequency of 20 Hz, topmost average power of 200 W, and pulse duration in the range 0.5–20 ms is applied for the laser process. Schematically, the diagram of the laser surface modification process is illustrated in Fig. 1. Prior to applying the laser process, H13 samples were austenitized in 1025 °C for 20 min and then quenched in the oil followed by heat treatment in 560 °C for 1.5 h. To eliminate the oxide scales and enhance the operation of the laser beam on the surface, H13 heat-treated samples were polished repeatedly with SiC sandpaper, starting from 60–100 grade size, and rinsed with deionized water. The pre-layer paste (the mixture of TiC powders and sodium silicate paste (Na_2SiO_3)) with the ratio of Wt%TiC/Wt%Paste = 3/2 is used to the H13 samples surface. The commercial TiC powder with a mean particle size of 1 μm was used. A pulse Nd:YAG laser with operational characteristics shown in Table 2 and maximum power of 220 W was utilized to produce the composite area.

Investigation of morphology is performed using a field emission scanning electron microscope (FESEM, Mira3-XMU) and scanning electron microscopy (SEM, TeScan Roventec vega II xmu), equipped with energy-dispersive X-ray spectroscopy (EDS). Investigation of the crystal structure of H13-TiC composite is determined by Philips

2.2 Design of experiments

Response surface methodology or briefly RSM is defined as an ensemble of mathematical and statistical equations via empirical modelling of experimental variables in the interval specified. The purpose of using the method is to analyze the influence of the independent variables on a desired response [32].

In this work, the Box-Behnken Criterion was used for optimization of the independent variables which provide the best protection of H13-TiC surface composite. Forasmuch as this criterion is put forward to vary with three levels per factor [33], it is necessary to let a conversion action of independent variables (Z_1 , Z_2 and Z_3) to coded values of (1, 0 and + 1) according to the relationships (1–3) [34]:

$$X_i = \frac{(Z_i - Z_i^0)}{\Delta Z_i^0} \quad (1)$$

$$Z_i^0 = \frac{(Z_i^{\max} + Z_i^{\min})}{2} \quad (2)$$

$$\Delta Z_i^0 = \frac{(Z_i^{\max} - Z_i^{\min})}{2} \quad (3)$$

where Z_i represents the actual value of variable. ΔZ_i^0 and Z_i^0 are signified as the step change and the center point of actual value of variables, respectively. $Z_i^{\max}$ and $Z_i^{\min}$ represent the maximum and minimum of the actual value of the variables, respectively. X_i is the coded value of independent variables. In general, the purpose of using RSM is to reduce the cost of the laboratory analysis. Otherwise

speaking, the independent variables are assumed at the range of $(-1, 1)$ to estimate many experimental results which have not been executed [34]. In Table 3, independent variables and the corresponding coded values are described. To make a set of second-order response surfaces, the variation of microhardness of the composite area as response of interest under different conditions of independent variables is applied. The following is a summary of Table 4. In Eq. (4), the response as a function of three independent variables is given:

$$Y = f(X_1, X_2, X_3) + \varepsilon \quad (4)$$

where Y and ε represent the dependent variable and bias, and X_i are defined as independent variables. The results summarized in Table 4 are fed into Design Expert 8.0.7.1 software package to find mutual relationships among three independent variables based on the Eq. (5):

$$Y = \beta_0 + \sum_{i=1}^k \beta_i X_i + \sum_{i=1}^k \beta_{ii} X_i^2 + \sum_{i=1}^k \sum_{j=2}^k \beta_{ij} X_i X_j + \varepsilon \quad (5)$$

where X_i and X_{ij} are the coded values. So, the predicted response is affected by coded values and the set of regression coefficients: β_0 (intercept coefficient), β_i (linear

coefficients), β_{ii} (quadratic coefficients), β_{ij} (interaction coefficients) and ε is bias.

3 Result and discussion

3.1 Phases and microstructure

According to Fig. 2, which demonstrates the X-ray diffraction pattern of the composite region, it can be stated that the deposited carbides within the composite zone are located in a ferritic field. Given that the Ti element in ferrous alloys is a ferrite stabilizer, the melting of TiC particles in the molten pond has led to an increase in the Ti content of the melt in the treated area. Figure 3 is an SEM image of the cross-sectional view of the composite region. As seen, the composite region contains hard TiC particles evenly distributed within ferritic field.

3.2 Effect of scanning speed on the microstructure of the treated region and HAZ

The laser beam scanning speed introduces as one of the most important variables in the laser process. For this purpose, in this paper, the scanning speed was investigated

Table 3 Characteristics of the independent variables

Parameters	Symbol		Levels					
	Actual	Coded	Actual			Coded		
Scanning speed (mm/s)	Z_1	X_1	2	7	12	-1	0	1
Pulse Width (ms)	Z_2	X_2	6	8	10	-1	0	1
Operational distance (mm)	Z_3	X_3	4	5	6	-1	0	1

Table 4 Box-Behnken design matrix for investigation of independent variables according to actual and coded values

Run no	Actual value			Coded value			Hardness (HV)
	Z_1	Z_2	Z_3	X_1	X_2	X_3	
1	7	8	5	0	0	0	1310
2	7	8	5	0	0	0	1297
3	7	6	6	0	-1	1	1266
4	12	10	5	1	1	0	1605
5	7	8	5	0	0	0	1314
6	7	6	4	0	-1	-1	1210
7	7	10	4	0	1	-1	1403
8	2	6	5	-1	-1	0	896
9	12	8	4	1	0	-1	1530
10	2	10	5	-1	1	0	1186
11	7	10	6	0	1	1	1439
12	12	6	5	1	-1	0	1483
13	2	8	4	-1	0	-1	984
14	2	8	6	-1	0	1	1095
15	12	8	6	1	0	1	1551

Fig. 2 demonstration of XRD Patterns in the composite area

Fig. 3 SEM image of the cross-sectional view of the composite region

in three states of 2, 7 and 12 mm/s. Figure 4 depicts the SEM image of the cross-sectional view of the treated layer at different scanning speeds. As can be seen, the depth and width of the treated area as well as the HAZ decreased with increasing laser beam scanning speed. The laser scanning speed has a great impact on process physics and the changes in the process scanning speed lead to a change in the pulse's overlap rate, input energy to the component and the interaction time between the laser beam and

surface. According to Eqs. (6), (7) and (8), with increasing scanning speed, on the one hand, the overlap rate of the pulses decreases resulting a decrease in the input energy or in other words, the amount of heat produced. On the other hand, with increasing scanning speed, the amount of energy per unit length decreases giving rise to a reduction in the interaction time between the laser beam and the substrate surface, resulting in a reduction of the temperature in the molten pool. The decrease in the melt pool temperature led to a reduction in the volume of the melted area, thus decreasing the depth and width of the treated area and the HAZ [35–37].

$$O_f(\%) = \left(1 - \frac{v/f}{D + v\tau}\right) \times 100 \quad (6)$$

$$E = \frac{P}{v} \quad (7)$$

$$t_i = \frac{D}{v} \quad (8)$$

where O_f is the overlapping factor, D is laser beam diameter (mm), v is scan velocity (mm/s), τ is the pulse width (s), f is the laser pulse frequency (1/s), E is the Average energy received per unit length (J/mm), P is the average power (W) and t_i is the time of laser beam interaction with the substrate surface. Increasing the scanning speed of the laser beam reduces the heat of the molten pond, thus

Fig. 4 SEM cross-sectional images of H13-TiC pulse laser composite area at operational distance of 4 (mm) and pulse width of 8 (ms), **a** scanning speed of 2 (mm/s), **b** scanning speed of 7 (mm/s), **c** scanning speed of 12 (mm/s)

the dissolved TiC content in the molten pond decreases, so the morphology of TiC particles, with increasing scanning speed, remains the same as the original morphology with little change. Reducing the scanning speed increases the dissolution of TiC particles, and consequently, after solidification, inside the microstructure, the re-frozen carbides are a combination of titanium carbide and alloying elements of the matrix phase, which are observed with dendritic, spherical and rod morphologies. As the dissolution rate of TiC particles in the molten pond increases, the sphericity increases the surface free energy, thus these particles appear in the microstructure in the forms of cubic, polygonal, layered, dendritic and petal in order to decrease the surface free energy. Figure 4 demonstrates the FESEM image of the mid-cross section in the treated layer at different scanning speeds [38]. According to Fig. 5a and Eqs. (6)–(8), it is observed that due to the high laser beam scanning speed and, consequently, the lower interaction time between the laser beam and the substrate surface, less heat enters the component and the dissolution of TiC particles is negligible. For this reason, TiC particles are distributed uniformly in the treated region, almost the same as the initial morphology in Fig. 5(a). In Fig. 5b, the lower the scanning speed, the longer the interaction time between the laser beam and the substrate surface, thereby increasing the input heat, leading to an increase in the dissolution of TiC particles in the molten pool. As shown in Fig. 5b, due to the local dissolution of the primary carbides, they are smaller in size and more spherical in morphology. In Fig. 5c, the laser beam scanning speed is at its lowest, and almost all the primary carbides are dissolved, therefore in this state, the carbides have the highest density in the molten pool, and after freezing, are deposited with dendritic morphology to reduce surface free energy. Looking more precisely at Fig. 5c, it is observed that the carbides have grown with a dendritic morphology and are

surrounded by very fine secondary carbides in the form of rods and spheres [38–42].

In general, in laser operations, the materials added to the molten pool dissolve in part or in whole and precipitate with the same chemical composition or with the formation of new phases during cooling. Also, carbide particles that are produced in situ in laser operations have different shapes. The morphology of the re-precipitated carbides changed from spherical to cubic, petal, rod (pseudo-dendritic) and dendritic ones to minimize the surface free energy [38, 42].

Further explanation is that by the interaction of the laser beam and the materials, heat is transferred to the steel surface through the pre-placed layer and melts it. The molten pool rotates due to the difference in surface stresses resulted from the temperature gradient [40]. According to the rotation of the melt due to changes in surface stress and buoyancy forces, TiC particles are dispersed in the pool and mainly dissolve in it. As the pond cools, TiC precipitates as the initial phase of the melt. High cooling rate and fluctuation of chemical composition in the molten pool cause the development of various forms of TiC deposits. It should be noted that the intrinsic properties and freezing conditions determine how the final growth and shape of TiC particles in the microstructure [40, 41]. Based on classical thermodynamics, the preferred crystal shape is defined by minimizing surface energy [42].

3.3 Effect of laser pulse width on the microstructure of the treated area and HAZ

Figure 6 shows a scanning electron microscope image of the cross-sectional views of the treated layer at the pulse speeds of 6, 8 and 10 ms. As can be seen, with increasing laser pulse width, the depth and width of the treated area and the HAZ decrease. As with the laser beam scanning

Fig. 5 SEM images of H13-TiC pulse laser composite area at operational distance of 4 (mm) and pulse width of 8 (ms), at the scanning speeds of **a** 12 (mm/s), **b** 7 (mm/s), **c** 2 (mm/s)

speed, the pulse width has a great impact on the process physics. The changes in the laser pulse width will change the maximum amount of input power to the component, laser intensity, laser beam irradiation time, and consequently, input heat to the component. According to Fig. 6 and Eqs. (9) and (10), with increasing pulse width, the maximum power and intensity of the laser beam applied to the surface decreased, reducing the heat and volume of the molten pool formed on the surface of the component. Therefore, the depth and width of the treated area and HAZ decreased [43, 44].

$$PP = \frac{PE}{\tau} \quad (9)$$

$$I_0 = \frac{PP}{r^2 \pi} \quad (10)$$

where PP is the maximum power (KW), PE is the pulse energy (J), I_0 is laser beam intensity, τ is the pulse width (s) and r is the laser beam radius. Figure 7 displays SEM images of the treated layers' mid-cross sections at diverse pulse widths. As clearly seen, the decrease in pulse width, on one hand, increased the dissolution of TiC particles, while on the other hand, reduced the particle size of the carbides that were dissolved and re-frozen. By comparing Fig. 7b and c, it can be seen that the size of dendritic and bar-shaped carbids decreased due to a decrease in the pulse width. With increasing pulse width, the temperature of the melt pool decreased, resulting in a decrease in the dissolution of TiC particles, which is clearly deduced

Fig. 6 SEM cross-section images of H13-TiC pulse laser composite area at operational distance of 5 (mm) and scanning speed of 2 (mm/s) and the pulse widths of **a** 6 (ms), **b** 10 (ms)

by comparing Fig. 7a, b, c. According to Fig. 7 and Eq. (11), decreasing the pulse width reduces the laser beam irradiation time, which increases the temperature gradient ($\partial T/\partial X$) in the treated region and also increases the cooling rate ($\partial T/\partial t$). Therefore, dissolved carbides become smaller in size with any morphology after being frozen [43].

$$t_L = f \times \tau \quad (11)$$

where t_L is the Laser beam irradiation time and f and τ are previously defined.

3.4 The effect of laser beam operational distance on the microstructure of the treated area and HAZ

Figure 7 demonstrates a SEM image of the cross-sectional view of the treated layer at operational distances of 4, 5 and 6 mm. As seen, the reduction in the laser beam operational distance, on one hand, increased the depth of the treated area and the HAZ, while on the other hand, reduced the width of the treated area. Changes in the operational distance lead to a change in the amount of overlap of the pulses, the overlapped area and the interaction time between the laser beam and surface area. According to Fig. 8 and Eqs. (12), (13) and (14), with increasing operational distance, the overlap rate of the pulses and area of the overlapped region increased, resulting an increase in the width of the treated region [36, 39].

By decreasing the operational distance, resulting in the reduction of the laser beam focusing areas on the surface of the component, the width of the treated area reduced, but due to the penetration of heat into the inner part of the component, the depth of the treated area and HAZ increased.

$$A_0 = 0.25D^2(2\theta - \sin 2\theta) \quad (12)$$

$$\theta = \cos^{-1} \left(\frac{D-d}{D} \right) \quad (13)$$

$$d = \frac{((f-1)D - v)}{(f-1)} \quad (14)$$

where A_0 is the overlap area (mm^2), D is laser beam diameter (mm) and d is the laser pass overlap distance.

Figure 9 displays the SEM image from the mid-cross section of the composite area at different operational distances. As seen, the decrease in laser beam operational distance, on one hand, increased the dissolution of TiC particles and altered the initial morphology of the particles, while on the other hand reduced the size of the carbides that again precipitated with different morphologies.

According to Fig. 9, reducing the operational distance reduces the overlap of the pulses and the overlapped surface, thereby reducing the effect of pre and post heat in the treated area. On the other hand, according to Eq. (3),

Fig. 7 SEM images of H13-TiC pulse laser composite area at the operational distance of 5 (mm) and scanning speed of 2 (mm/s), and the pulse widths of **a** 10 (ms), **b** 8 (ms), **c** 6 (ms)

the interaction time between the laser beam and the surface of the component also decreases, and therefore the cooling rate increases. Hence, the primary carbide particles melted in the melt pool created by applying the laser beam on the surface and the localized concentration of

the melt pool heat, precipitated at the smaller sizes than the longer operational distances [35, 36, 43].

Fig. 8 SEM cross-sectional images of H13-TiC pulse laser composite area at the pulse width of 8 (ms) and scanning speed of 12 (mm/s), and operational distances of **a** 6 (mm), **b** 4 (mm)

3.5 Optimization of composite coating microhardness

A second-order response relation as shown in Eq. (15) is used to estimate the relationship between microhardness response and variables:

$$Y (\text{microhardness}) = 1307 + 251X_1 + 97.25X_2 + 28X_3 - 42X_1X_2 - 22.5X_1X_3 - 5X_2X_3 - 27X_1^2 + 12.5X_2^2 + 10X_3^2 \quad (15)$$

where X_1 , X_2 and X_3 are the coded values and Y is dependent variable (microhardness). For investigating the validity in order to predict microhardness, the response surface equation has been performed with results from ANOVA. The results are given in Table 5. The R^2 value is 0.987, which indicates that 98.7% of the data fit the equation, and the 0.0001 value for the p value indicates that this relationship is effective.

Figure 10 shows the diagrams examining the effect of scanning speed, pulse width and laser beam operational distance on the microhardness of the composite region.

According to Fig. 10, results of ANOVA in Table 5 and the results and analyses presented in relation to the study of the effect of laser process variables on the microstructure of the treated area, it can be stated that by reducing the laser beam scanning speed, the amount of thermal energy that enters the component increases, thus the temperature of the molten pool also increases, resulting an increase in the dissolved TiC content.

Since the new carbides that have been deposited again in the composite area are a combination of titanium carbide and alloying elements of the matrix phase, they, therefore, have a lower hardness than the original titanium carbide. Hence, with reducing the laser beam scanning speed, the hardness of the treated area is reduced.

As the pulse width increases, the maximum power and intensity of the laser beam applied to the surface decreases, which results in the dissolution of TiC particles in the melt pool and thus increases the hardness in the area.

Increasing the operational distance results in the thermal energy of the laser beam being applied to a larger surface area, which results in a decrease in the temperature of the molten pond. The result is an increase in the hardness of the composite area.

4 Conclusion

1. With increasing the laser beam scanning speed, the overlap of the pulses is reduced and the amount of the thermal energy absorbed by the component is decreased. As a result, the temperature of the melt pool decreases giving rise to the reduction of the depth and width of the composite area and the depth of the HAZ region. In addition, the hardness of the composite region is increased as a result of decreasing the dissolved TiC content.

Fig. 9 SEM images of H13-TiC pulse laser composite area at the pulse width of 8 (ms) and scanning speed of 12 (mm/s), and the operational distances of **a** 6 (mm), **b** 5 (mm), **c** 4 (mm)

- Increasing the pulse width leads to a reduction in the maximum power, intensity of the laser beam applied to the surface and heat of the melt pool resulting in the reduction of the dissolution of TiC particles in the

melt pool and therefore, increasing the hardness of the composite area.

- Increasing the operational distance causes the thermal energy of the laser beam to increase and therefore a larger surface area of the component to be subjected. This, in turn, results in a decrease in the heat of the formed molten pool, decreasing the amount of non-melted TiC particles, followed by an increase in the hardness of the composite area.
- Laser process variables to access the composite surface with optimum microstructure and microhardness properties are optimized using the optimization phase

Table 5 the results of ANOVA for model of microhardness

Item	Degrees of freedom	Mean square	F-Value	P-Value	R ²
Modelled value	9	66,561.9	532.92	0.0001	0.987

Fig. 10. 3D and contour plots of the effect of pulse width, scanning speed and operational distance of the pulse laser beam on microhardness of composite areas **a** and **b** pulse width of 6 (ms), **c** and **d** pulse width of 8 (ms), **e** and **f** pulse width of 10 (ms)

of the RSM experiment design technique and mathematical equations are provided for all the responses defined in this design. The optimum condition of the

laser process variables is when the scanning speed is 12 mm/s, pulse width is 9.96 ms and operating dis-

tance is 5.94 mm, in which case the microhardness of the composite surface is 1606 Vickers.

Compliance with ethical standards

Conflict of interest statement The authors declare that there is no conflict of interests regarding the publication of this paper.

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