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Modeling of Laser Transformation Hardening Parameters of Commercially Pure Titanium

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ABSTRACT

This research paper represents the application of Response Surface Methodology (RSM) and Box-Behnken design (BBD) for modeling and an analysis of the influences of dominant Laser transformation hardening parameters: laser power (LP), scanning speed (SS) and focused position (FP) on hardened bead geometries such as hardened bead width (HBW) and hardened depth (HD) of laser hardened surface quality of unalloyed titanium sheet of 1.6 mm thickness, nearer to ASTM Grade 3 of chemical composition using CW 2kW Nd:YAG laser. The effects of laser power, scanning speed and focal point position on the hardened-bead geometry (i.e. hardened bead width (HBW) and hardened depth (HD) were investigated using response surface methodology (RSM). Linear and quadratic polynomial equations for predicting the hardened bead geometry were developed. The results indicate that the developed mathematical models predict the responses adequately within the limits of hardening parameters being used. It is proposed that regression equations can be used to find optimum hardening conditions for desired criteria.

Keyword: *Laser Transformation Hardening; RSM; Box-Behnken design; unalloyed titanium; hardened-bead profile*

1. INTRODUCTION

Titanium and its alloys are extensively used in the aeronautical industry, medicine and engineering industry due to their specific properties such as light weight, high strength-to weight ratio, corrosion resistance and excellent high temperature properties. Surface engineering of titanium alloy components provides means by which the desirable bulk properties may be retained in conjunction with enhanced wear resistance [1, 2].

LSTH allows obtaining a hardened surface layer in titanium and its alloys by changing the base structure into hardened transformed beta martensite. Hardenability of titanium and its alloys is a phrase that refers to its ability to permit full transformation of the titanium and its alloys to transform beta (martensites, alpha) or to retain beta to room temperature [3−4].

Many researchers have used the Box-Behnken design and Response surface methodology in developing the mathematical models of process parameters of laser welding, grinding and metal cutting operations etc. In this paper, authors made an effort in developing the empirical relationship between laser transformation hardening parameters and hardened bead geometry responses of unalloyed titanium using Box-Behnken design matrix and Response Surface Methodology. Olab et al. investigated the Laser butt-welding of medium carbon steel using CW 1.5 kW CO2 laser by Response Surface Methodology (RSM). The experimental plan was based on Box-Behnken design [5]. N. Aslan and Y. Cebeci proved that Box-Behnken design and response surface methodology could efficiently be applied for modeling of grinding of some Turkish coals [6]. Yi Liu et al. were employed Response surface methodology to optimize the adsorption parameters of Methylene Blue onto a chitosan-g-poly (acrylic acid)/halloysite hydrogel composite with 50% halloysite content [7]. Vinod Kumar developed mathematical models for SAW using developed fluxes using Box Behnken design and used the Response surface methodology to predict critical dimension of the weld bead geometry and shape relationships [8]. Siva Prasad K. et al. stated the Application of design of experiments, Response surface Methodology, and use of Box-Behnken Design to plasma Arc Welding Process [9]. Mayank Mittal and Dheerendra K Dwivedi presented a systematic study on the effect of input process parameters of the weld-bonding process, namely curing temperature, curing time, welding pressure, welding time and welding current, on the characteristics of the weld bonds, such as bond-line thickness, equivalent nugget diameter, corona size and ultimate shear tensile strength using a Box–Behnken design approach[10]. C. Anand Chairman et al. performed the experimental trials based on Box-Behnken design which comes under Response Surface Methodology (RSM) and investigated the two-body abrasive behavior of titanium carbide filled glass fabric-epoxy composites [11]. Prakash S et al. have been used Box-Behnken design and RSM model successfully to determine the surface roughness attained by the drilling of MDF panels for various input parameters namely feed rate, speed and drill diameter [12].

The main objective of this research paper to investigate and develop the empirical relationship between the laser transformation hardening parameters and laser hardened bead profile responses such as hardened bead width and hardened depth of unalloyed titanium using RSM and multiple regression analysis.

2. EXPERIMENTAL DESIGN

The experiment was designed on a three level Box-Behnkin design with full replication [13]. Laser power (750-1250 Watts), scanning speed (1000-3000 mm/min) and focused position (-30 to -10 mm) being the laser independent input variables. Box-Behnkin designs are response surface designs specially made to require only 3 levels, codes as -1, 0, and +1. Table 2 shows laser input variables and experimental design levels used.

A response surface method (RSM) has often been applied to optimize the formulation variables [14, 15]. The optimization procedure based on RSM includes statistical experimental designs, multiple regression analysis, and mathematical optimization algorithms for seeking the best formulation under a set of constrained equations. RSM was applied to the experimental data using statistical software, Design- expert 7. Linear and second order polynomials were fitted to the experimental data to obtain the regression equations. The sequential F-test, lack-of – fit test and other adequacy measures were used in selecting the best models. A step-wise regression method was used to fit the second order polynomial equation (1) to the experimental data and to identify the relevant model terms [16, 17]. The same statistical software was used to generate the statistical and response plots.

$$Y = b_o + \sum b_i x_i + \sum b_{ii} x_{ii}^2 + \sum b_{ij} x_i x_j \quad (1)$$

3. EXPERIMENTAL METHODOLOGY

Primarily, experimental bead on trials were conducted on a given unalloyed Titanium alloy substrate with chemical composition given in Table 1. The chemistry is nearer to ASTM Gr. 3. The thickness of the substrate selected is 1.6 mm, in order to motivate encourage the majority of the industrial applications that is in practice at present. For conducting the experiments on the substrate, the materials surface is cleaned properly with suitable agents.

Table 1. Chemical composition of commercially pure Titanium

Ele.	Ti	C	Fe	V	Cu	O	N	Al
% by Wt	Bal.	0.011	0.15	0.029	0.14	0.1	0.003	1.1

Table 2. Process Variables and Experimental Design Levels Used

Variables	-1	0	+1
Laser power, LP(Watts)	750	1000	1250
Scanning speed, SS (mm/min)	1000	2000	3000
Focused position, FP (mm)	-30	-20	-10

Figure.1. Solid state Nd:YAG Laser source at WRI used for experimental work [18].

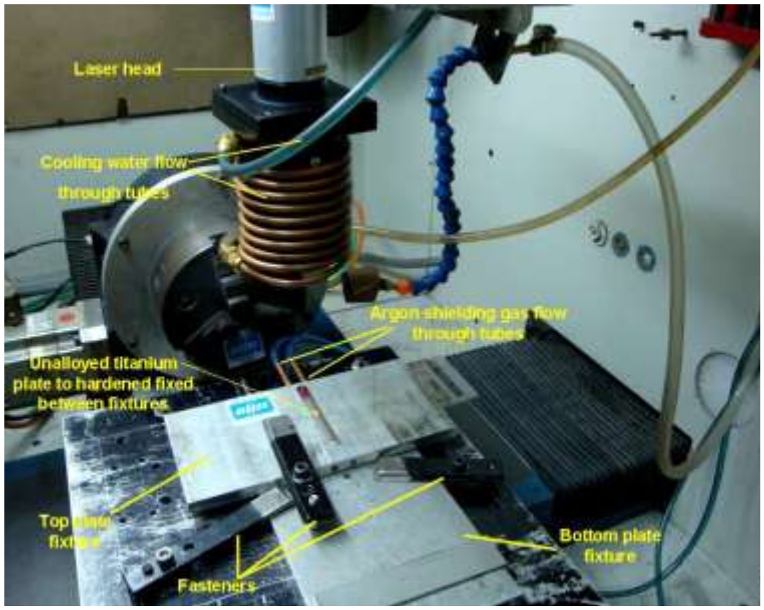

Figure.2. Experimental set-up showing the laser beam head and shielding gas arrangements in the working chamber [18].

A continuous wave (CW) 2KW, with radiation wavelength λ=1.06μm Nd: YAG laser source from GSI Lumonics is employed for the experimental work as shown in Figure.1. The experiment was carried out according to the design matrix in a random order to avoid any systematic error. A spherical beam configuration is used throughout for the study. The experiment set up is shown in Figure. 2. The laser beam is transported through a fibre optic cable to the work centre. Siemens 802 CNC controller is providing the process control during the experiments. The work centre is having x, y and rotational movement for processing applications. The laser source, work centre and the controls are interfaced. Cooling is ensured by a chiller and a cooling tower. For the study, 120mm focal optic is employed with varying beam spot size depending on defocus distance to obtain a wider scan area. Argon gas is employed as shielding medium with a constant flow rate of 8lpm throughout the experimental work. Transverse sectioned specimens were cut from laser hardened bead-on trial of unalloyed Titanium sheet having 1.6 mm thickness and mounted. Standard metallographic was made for each transverse sectioned specimens. The bead profile parameters 'responses' were measured using an optical microscope with digital micrometers attached to it with an accuracy of 0.001 mm, which allow to measure in x-axes and y-axes.

The measured laser hardened bead profile parameters 'responses' were recorded as per the design matrix shown in Table 3.

4. RESULTS AND DISCUSSION

The results of the laser hardened-bead profile were measured according to the design matrix with coded independent process variables in Table 3 and recorded. Analyzing the measured responses by the Design-expert software, the fit summary output indicates that the linear model is significantly significant for hardened bead width. While for the other response hardened depth the quadratic model is statistically recommended for further analysis.

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	1.2231	3	0.4077	157.3093	< 0.0001	Sig.
LP	0.6699	1	0.6699	258.4824	< 0.0001	
SS	0.5045	1	0.5045	194.6655	< 0.0001	
FP	0.0487	1	0.0487	18.78011	0.0008	
Residual	0.0337	13	0.0026			
Lack of Fit	0.0227	9	0.0025	0.922208	0.5804	Not sign.
Pure Error	0.011	4	0.0027			
Corrected Total	1.2568	16				

3. Design Matrix with code independent process variables

Exp. No	Run order	Laser power (Watts)	Scanning speed (mm/min)	Focused position (mm)
1	14	-1	-1	0
2	1	1	-1	0
3	4	-1	1	0
4	8	1	1	0
5	3	-1	0	-1
6	5	1	0	-1
7	6	-1	0	1
8	16	1	0	1
9	10	0	-1	-1
10	13	0	1	-1
11	7	0	-1	1
12	15	0	1	1
13	12	0	0	0
14	11	0	0	0
15	9	0	0	0
16	17	0	0	0
17	2	0	0	0

Table 4. ANOVA table for the hardened bead width reduced linear model

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	0.9284	5	0.1857	61.4275	< 0.0001	Sig.
LP	0.2309	1	0.2309	76.3746	< 0.0001	
SS	0.6166	1	0.6166	203.989	< 0.0001	
FP	0.0164	1	0.0164	5.4191	0.0400	
A×B	0.0195	1	0.0195	6.43796	0.0276	
B^2	0.0451	1	0.0451	14.9169	0.0026	
Residual	0.0333	11	0.003			
Lack of Fit	0.0153	7	0.0022	0.48566	0.8099	Not sig.
Pure Error	0.018	4	0.0045			
Corrected Total	0.9616	16				

Std. Dev.	0.0509	R-Squared	0.9732
Mean	2.2522	Adj R-Squared	0.9670
C.V. %	2.2604	Pred R-Squared	0.9533
PRESS	0.0587	Adeq Precision	43.775

Table 5. ANOVA table for hardened depth reduced quadratic model

Std. Dev.	0.0549	R-Squared	0.9654
Mean	0.6370	Adj R-Squared	0.9497
C.V. %	8.63099	Pred R-Squared	0.9069
PRESS	0.0895	Adeq Precision	27.4010

4.1. Analysis of variance (ANOVA)

The adequacy of the developed mathematical models were tested using the analysis of variance (ANOVA) technique and the results of the linear and quadratic order response surface model fitting in the form of analysis of variance(ANOVA) are given in Tables 4-5. The test for significance of the regression models, the test for significance on individual model coefficients and the lack-of-fit test were performed using the same statistical Design-expert 7 software package. By selecting the step-wise regression method, which eliminates the insignificant model terms automatically, the resulting ANOVA Tables 4-5 for the response surface quadratic models summarize the analysis of variance of each response and show the significant model terms.

The values of "Probability > F" in Tables 4-5 for all models are less than 0.0500 indicate that all models are significant. In all cases the "Lack-of-fit" values implies the "Lack-of-fit" is not significant relative to the pure error. Non-significant lack- of- fit as it is desired and it is good.

Initially, for the hardened bead width (HBW) model, from the Table 4 the analysis indicated that there is a linear relationship between the main effects of the three process parameters. In the case of hardened depth (HD) model, from the Table 5 the main effect of laser power (LP), scanning speed (SS), focused position (FP), interaction effect of laser power (LP) with scanning speed (SS) and the second order effect of scanning speed (SS) have the significant effect. However, the main effect of scanning speed (SS) and the main effect laser power (LP) are the most significant factors associated with the hardened bead width (HBW) as compared to focused position (FP).

The final mathematical models in terms of coded factors as determined by design expert software are shown below:

Hardened bead width (HBW) = $2.2522 + 0.2894\times LP - 0.251\times SS - 0.078\times FP$ (2)

Hardened depth (HD) = $0.5884 + 0.1698 \times LP\ 0.2776\times SS0.0452\times FP\text{-}\ 0.0697\times LP\times SS+0.1032\times SS^2$ (3)

While the following final empirical models in terms of actual factors:

Hardened bead width (HBW) = $1.44098 + 0.00115\times LP - 0.00025\times SS - 0.0078\times FP$ (4)

Hardened depth (HD)=$0.4094+0.00123\times LP-0.00041\times SS+0.00452\times FP-2.79E\text{-}07\times LP\times SS+1.032E\text{-}07\times SS^2$ (5)

4.2. Validation of the models

Figures. 3-4 shows the relationship between the actual and predicted values of the hardened bead width (HBW) and hardened depth (HD) respectively. These Figures indicate that the developed models are adequate because the residuals in prediction of each response are minimum, since the residuals tend to be close to the diagonal line. Furthermore, to verify the adequacy of the developed models, five confirmation experiments were carried out using new test conditions, but are within the experimental range defined early. Using the point prediction option in the software, the HBW and HD of the validation experiments were predicted using the previous developed models.

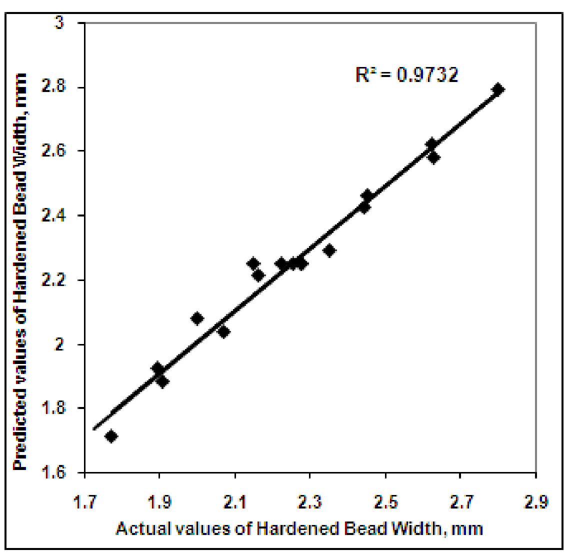

Figure.3. Actual/Predicted values of Hardened Bead Width.

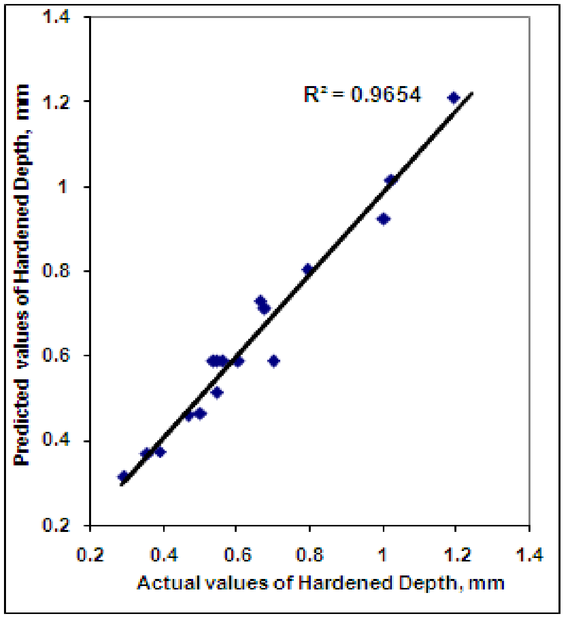

Figure.4. Actual/Predicted values of Hardened Depth.

4. CONCLUSIONS

In the present study, laser transformation hardening of unalloyed titanium was studied and the following conclusions were drawn:

1. Two models were developed for predicting the heat input (Hi), hardened bead width (HBW), hardened depth (HD) of the laser transformation hardened unalloyed titanium using response surface methodology (RSM).
2. Box-Behnken design can be employed to develop mathematical models for predicting laser hardened-bead geometry.
3. The desired hardened depth and width with high quality of laser transformation hardening (LTH) can be by choosing the working condition using the developed models.
4. It is investigated that, in case of laser transformation hardening (LTH), as scanning speed increases, as the depth of hardening decreases and vice-versa, but we are concentrating on desired optimum minimum depth. Therefore, both scanning speed and laser power have positive effect on all the responses investigated.
5. Bead width as well as depth of hardening linearly decreases with increasing scanning speed.
6. It is evident that the bead geometry provides a useful tool to manipulate the hardened bead width and hardened depth during LTH. It is clearly observed that the hardened width linearly increases defocused beam i.e. with higher beam spot size. Depth of hardened surface increases linearly with decrease in defocused position from -30 mm to -10 mm.

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