Application of Taguchi Approach and Utility Concept in Multi-Objective Optimization of Laser Transformation Hardening of Commercially Pure Titanium for Heat Input and Tensile Strength

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Abstract

This research article primarily focuses on multiperformance optimization of tensile strength and of laser transformation hardening of commercially pure titanium sheet of ASTM Gr.3 with thickness being 1.6mm Using Taguchi Methodology and Utility Concept using a continuous wave (CW) 2kW, solid-state Nd:YAG laser. Taguchi optimization method for simultaneous minimization of heat input (HI) and tensile strength (σ) is influenced by laser transformation hardening parameters: laser power (LP), scanning speed (SS), and focused position (FP) of laser transformation hardened commercially pure titanium. The effect of these process parameters on the heat input (HI) and tensile strength (σ) properties of commercially pure titanium and subsequent optimal settings of the process parameters have been obtained using Taguchi's parametric design approach and utility concept. The response performance is analyzed based on signal-to-noise ratio and analysis of variance (ANOVA). The optimal levels of the laser process parameters were determined through the Analysis of Means (ANOM). The results demonstrate that the scanning speed (SS) and the laser power (LP) are the significant parameters in deciding the tensile strength and heat input of laser transformation hardened commercially pure titanium. The confirmation tests with optimal levels of laser process parameters were carried out to demonstrate the effectiveness of Taguchi optimization method. The optimization results revealed that a combination of higher levels of scanning speed (SS) and focused position (FP) i.e., increase in defocus along with laser power (LP) in the lower level play important role in order to simultaneously minimize the heat input (HI) and to maximize the tensile strength (σ). The predicted optimal values of tensile strength and heat input of commercially pure titanium sheet produced by laser transformation hardening process are 464 N/mm^2 and 141.667 Watts, respectively, for the optimized laser process parameters with minimum LP=750 Watts, maximum SS=3000mm/min, and lower value of FP=-30mm (increase in defocus).

Keywords: LTH; Nd: YAG laser; Taguchi method; Taguchi utility; S/N ratio; tensile strength; heat input.

1. INTRODUCTION

Surface hardening by inducing phase transformations through the heating effect of a laser beam is one of the first laser based fabrication methods to be commercialised, in the early 1970s. 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].

Laser transformation hardening (LTH) is an advanced heat treatment method to obtain hard, wear resistant layer on surface without affecting the bulk material through the interaction of laser and material. Compared to conventional methods, it has advantages such as low thermal distortion, less post-treatment work, good controllability of laser heat source and adaptability to geometry of component, etc. [3]. The low density, excellent high temperature mechanical properties and good corrosion resistance of titanium and titanium alloys have led to a diversified range of successful applications for the demanding performance and reliability requirements of the medical, aerospace, automotive, petrochemical, nuclear and power generation industries[4, 5].

When the operation temperature exceeds 130 °C, titanium alloys can be used as replacements for aluminium-based materials to achieve improved mechanical properties at elevated temperatures for applications such as the external shells of turbines, the power units for avionics and the landing gear structural components in Boeings 747 and 757 [6]. Alternatively, as titanium is exhibit very low corrosion rates in human body fluids as demonstrated, other applications that are relevant to the medical industry include prosthetic devices such as artificial heart pumps, pacemaker cases, heart valve parts as well as load bearing bone such as for hip bone replacement [7].

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 transformed

beta (martensites, alpha) or to retain beta to room temperature [8, 9]. The standard laser transformation hardening of titanium and its alloys involves two main steps: beta phase formation, in which the material is heated to/above the beta transus temperature, i.e., β-transus (888[O]C or 1621[O]F), in order to form the material with 100% beta phase (but below the melting point) and "self quenching" or cooling down, where β-phase is transformed into harder acicular (plate-like) α martensite (transformed β) or retain beta to room temperature. The β-transus is defined as the lowest equilibrium temperature at which the material is 100% beta or alpha, which does not exist. The β-transus is critical in deformation processing and in heat treatment. A correct treatment requires the heating stage be long enough for the β-phase formation to complete and allow the alloying elements such as, manganese, carbon, oxygen and nitrogen to stabilize it and dissolve iron, vanadium, molybdenum, copper, nickel, and silicon into the matrix. Self quenching should be fast enough so as to suppress the normal breakdown of β-phase into the initial α or α+ β phases and produce martensite instead.

The Taguchi method [10–12] is a systematic application of design and analysis for experiments. It has proved to be an effective approach to produce high-quality products at a relatively low cost. However, the original Taguchi method has been designed to optimize a single performance characteristic. Handling multiple performance characteristics by the Taguchi method requires further research [13, 14]. Trang et al. [15] used a fuzzy logic Taguchi method to optimize the submerged arc welding process and turning operations with multiple performance characteristics.

This paper illustrates the application of Taguchi method using the utility concept for multi-objective laser transformation hardening process optimization. The aim of this paper is to investigate and evaluate the optimal values of laser process parameters, such as laser power (LP), scanning speed (SS), and focused position (FP) for the simultaneous minimization and maximization of heat input and maximize the tensile strength respectively by Taguchi method and utility concept approach in laser transformation hardening of commercially pure titanium sheet of 1.6mm thickness using continuous wave (CW) Nd:YAG laser beam.

2. EXPERIMENTAL METHODOLOGY

2.1 Taguchi Approach

The performance of a product or process is characterized in terms of design and noise factors. Taguchi method utilizes a special design of orthogonal arrays to study the entire parameter space with only a small number of experiments. Experimental design using orthogonal arrays (OAs), recommended by Taguchi, not only minimize the number of treatments for each trial, but also keep the pair-wise balancing property. An OA is basically a matrix of rows and columns in which columns are assigned factors or their interactions and rows represent the levels of various factors for a particular experimental trial. The treatment combinations are chosen to provide sufficient information to determine the factor effects using the analysis of means. The orthogonal array imposes an

order on the way the experiment is carried out. The purpose of the Taguchi method is to identify the "optimal" settings of the controllable factors, not only to improve the product or process, but also to reduce the influence of the noise factors [16, 17]

The first step of designing an experiment with known number of factors in Taguchi's method is to select a most suitable OA, which design to cover all the possible experiment conditions and factor combination. The selection of which OA to use predominantly depends on these items in order of priority [18]:

1. The number of factors and interactions of interest,
2. The number of levels for the factors of interest, and
3. The desired experimental resolution or cost limitations.

To select a suitable orthogonal array for experiments, the total degrees of freedom need to be calculated. Basically, the degrees of freedom for the OA should be greater than or at least equal to those for the design factors. Once the levels of design factors have been settled, the Analysis of Means (ANOM) is conducted to find interaction of each factor on the objective value by calculating the mean of entire data of the design factors. Hence, the optimum level of each design factor can be found by focusing on its corresponding response graph. The Analysis of Variance (ANOVA) is then performed to determine the significant factors for the selected criterion. Finally, a prediction model consisting of the significant factors is built and confidence interval for estimated mean is constructed.

The performance measure, signal to noise ratio (S/N) proposed by Taguchi is used to obtain the optimum process parameter combinations. The larger S/N means the relation to the quality will become better [19]. The lower quality characteristic will be regarded as a better result when considering the smaller-the-best quality. The related S/N ratio is defined [20, 21] as:

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

where, n is the number of experiments for each experimental set and y1 expresses the quality experiment characteristic at the i-th experiment. On the contrary, the larger quality characteristic will have better result t when considering the larger-the-best quality; therefore, by taking the inverse of quality characteristic into Equation (1), the related S/N ratio can also be deduced and shown in Equation (2) [20,21].

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

2.2 Taguchi Approach with Utility Concept

In order to optimize the multiple responses, Taguchi design is

not applied directly, as each performance characteristic may not have the same measurement unit. Hence, the evaluations of various characteristics should be combined to give a composite index. Such a composite index represents the utility of a product. The overall utility of a product is the sum of utilities of each of the performance quality characteristics [22, 23]. If X_i is a measure of effectiveness of an attribute i and there are n attributes evaluating the outcome space, then the overall utility function is given by:

$$U(X_1, X_2, ... X_n) = \sum_{i=1}^{n} U_i(X_i) \tag{3}$$

where, $U_i(X_i)$ is the utility of the ith attribute. Depending upon the requirements, the attributes may be given priorities and weights. Hence, the weighted form of Equation (3) is:

$$U(X_1, X_2, ... X_n) = \sum_{i=1}^{n} \omega_i U_i(X_i) \tag{4}$$

where,

$$\sum_{i=1}^{n} \omega_i = 1 \tag{5}$$

and ω_i is the weight assigned to attribute i.

3. EXPERIMENTAL PROCEDURE

3.1 Plan of Experiments

The experiments were conducted on a given commercially pure titanium alloy base material with chemical composition shown in Table 1. The chemistry is nearer to ASTM Gr. 3. The thickness of the base material selected is 1.6 mm. Before conducting the experiments on the substrate, initially the materials surface is cleaned properly with suitable agents.

Table 1. Chemical composition of commercially pure Titanium.

Element	Titanium	C	Fe	Mo	H	Zr	O	N	Ti
% by Weight	Balance	0.10	0.20	0.003	0.015	0.0039	0.16	0.003	Balance

In this study a 2kW, continuous wave (CW) mode Nd:YAG laser beam device from GSI Lumonics is used as machining tool. Unlike the 10.6μm wavelength of the CO_2 laser beam, the wavelength of the Nd:YAG laser beam is only 1.064 μm. The low beam energy prevents the surface of the hardening area from overheating and ensures that the heat affected zone is small.

The experiment was carried out according to the Taguchi's L9 orthogonal array methodology design. A spherical beam configuration is used throughout for the study. 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 (i.e., focused position from -10, -20, -30mm) depending on defocus distance to obtain a wider scan area. Argon gas is employed as shielding medium with a constant flow rate of 10lpm throughout the experimental work. Transverse sectioned specimens were cut from laser hardened bead-on trial of commercially pure Titanium sheet having 1.6 mm thickness and mounted. Standard metallographic was made for each transverse sectioned specimens.

For the microstructure observation, the transverse section cut laser hardened specimens were ground with SiC paper up to 1500 grit, and then polished by 1 μm Al_2O_3 powder. The microstructure of the hardened surface observed using an optical microscope (with image processing computer controlled software) with digital micrometers attached to it with an accuracy of 0.001 mm, which allow to measure in x-axes and y-axes after the polished surface was acid etched by a solution of: Kroll's reagent–10ml of HF, 5ml HNO_3, 85 ml water; Procedure: Swab 3 to 20 seconds.

In the present work, three parameters, namely, laser power (LP), scanning speed (SS), and focused position (FP) are considered and the ranges of 750-1250W, 1000-3000mm/min, and -10 to -30mm respectively. The parameters identified in the present study are multilevel factors and their outcome effects are not linearly related; and hence, it has been decided to use three-level tests for the laser process parameters. The identified process parameters and their design levels are presented in Table 2.

Table 2. Process parameters and experimental design levels used

| Parameters/factors	Code	Unit	Levels		
			1	2	3
Laser power	LP	Watts	750	1000	1250
Scanning speed	SS	mm/min	1000	2000	3000
Focused position	FP	mm	-10	-20	-30

Taguchi optimization begins with the selection of orthogonal array with distinct number of levels defined for each of the parameters, laser power, scanning speed, and focused position. The minimum number of trials in the orthogonal array is given by:

$$N_{\min} = (l-1)k + 1$$

where, k = number of factors = 3 and l = number of levels = 3. This gives $N_{min} = 7$; and hence, according to Taguchi design concept L9 orthogonal array has been selected. Thus, only 9 experiments are required to study the entire laser transformation hardening process parameters space using L9 orthogonal array. The L9 orthogonal array along with the process parameters used for the present study is illustrated in Table 3.

Table 3. L9 orthogonal array along with the responses and computed values of multiresponse S/N ratio.

Serial No	Levels of process parameters			Responses		S/N ratio, dB		
	LP, Watts	SS, mm/min	FP, mm	HI, J/cm	σ, N/mm^2	η_1 for HI	η_2 for σ	Multiresponse η
1	1	1	1	450	444	-53.06	52.9477	-0.0583
2	1	2	2	225	457	-47.04	53.1983	3.0773
3	1	3	3	150	462	-43.52	53.2928	4.8855
4	2	1	2	600	442	-55.56	52.9084	-1.3273
5	2	2	3	300	453	-49.54	53.122	1.7898
6	2	3	1	200	459	-46.02	53.2363	3.6078
7	3	1	3	750	440	-57.50	52.8691	-2.3161
8	3	2	1	375	448	-51.48	53.0256	0.7725
9	3	3	2	250	455	-47.96	53.1602	2.6007
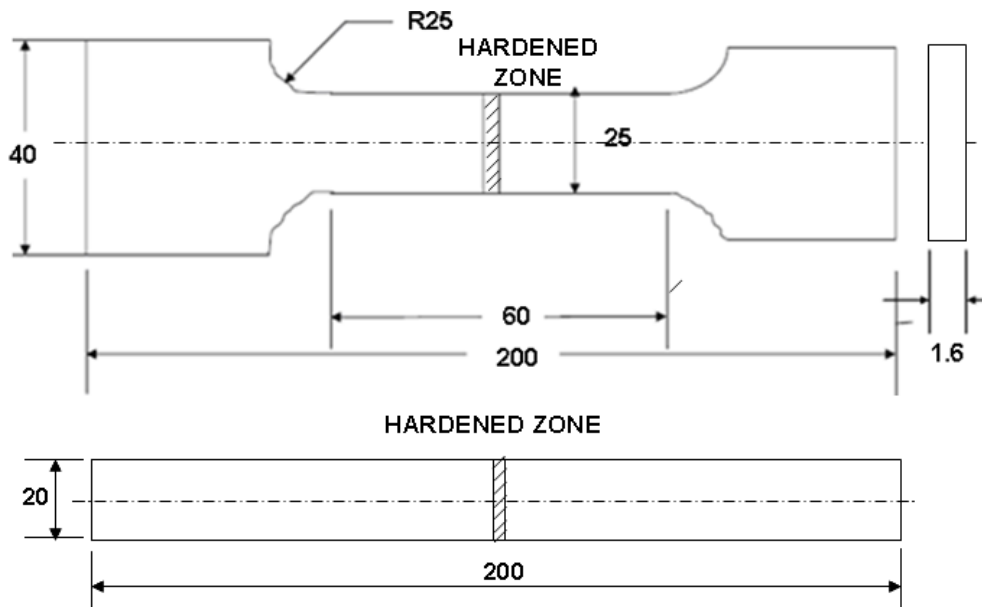
Figure 1. Schematic sketch of tensile test specimen, as per AWS B4.0

The schematic diagram of specimens which are used for tensile test and their dimensions are given in Fig.1. All the specimens were obtained in the same orientation from the laser hardened plate. The single pass laser beam transformation hardening experiments were conducted on a given commercially pure (CP Ti) or commercially pure titanium substrate. The thickness of the substrate selected is 1.6mm, to stimulate the majority of industrial applications that is in practice at present.

4. ANALYSIS OF RESULTS AND DISCUSSION

In the present study of laser transformation hardening process

optimization, the objective is to minimize the heat input and to maximize the tensile strength. The laser heat input (HI) is directly related to the laser power (LP) and scanning speed (SS). It can be calculated directly from the heat input (HI) = LP/SS.

The experimental values of heat input (HI) and tensile strength (σ) for each trial of an orthogonal array are summarized in Table 3. Taguchi design uses S/N ratio instead of mean value to interpret the trial results data into a value for the evaluation characteristic in the optimum setting analysis [5], because S/N ratio can reflect both mean and variation of the performance characteristics. In the present investigation, Taguchi parameter design with the utility concept has been introduced for optimizing the multiple performance

characteristics (HI and σ). Here, heat input (HI) is to be minimized and tensile strength (σ) to be maximized. Hence, ''smaller the better type'' characteristic for HI and ''larger the better type'' characteristic for σ have been selected. The S/N ratio associated with the responses, HI and σ are given as [5, 6]:

$$\eta_1 = -10\log_{10}(HI^2) \tag{6}$$

$$\eta_2 = -10\log_{10}\left\lfloor \frac{1}{\sigma^2} \right\rfloor \tag{7}$$

In the utility concept, the multiresponse S/N ratio is given by [16]:

$$\eta = \omega_1\eta_1 + \omega_2\eta_2 \tag{8}$$

where, ω_1 and ω_2 are the weighting factors associated with S/N ratio for each of the responses HI and σ, respectively. These weighting factors are decided based on the priorities among the various responses to be simultaneously optimized. In the present investigation, weighting factors of 0.5 for each of the responses is considered, which gives equal priorities to both HI and σ for simultaneous optimization. The computed values of S/N ratio for each response and the multiresponse S/N ratio for each trial in the orthogonal array are given in Table 3.

4.1 Analysis of Interaction Effects of Parameters on Multiple Performance Characteristics

The plots of two factor interaction effects on multiresponse S/N ratio of multiple characteristics are shown in Fig. 2-4. Fig. 2 shows the interaction effect of scanning speed and laser power. It can be observed from Fig. 1 that there exists a considerable interaction effect of scanning speed variation on multiresponse S/N ratio of performance characteristics for any given value of laser power. On the other hand, for any given laser power, the effect of scanning speed variation on multiresponse S/N ratio is comparatively less. Further, when the scanning speed is high (3000 m/min), the interaction effect due laser power is more as compared to the interaction effect when the scanning speed is either at low level (1000 m/min) or at medium level (2000 m/min). However, the interaction effect of scanning speed at 3000mm/min is high for all the laser power process levels and at 2000mm/min is high for laser power 1000, 1250 Watts as compared to the for the laser power 750 Watts scanning speed at 1000mm/min and 2000mm/min. Fig.3 illustrates the interaction effect of laser power and focused position. From the fig it is seen that the degree of mutual interaction between laser power and focused position on multiresponse S/N ratio of performance characteristics is more except for the laser power at lower level of 750 Watts at focused position -10mm. The interaction effect due to scanning speed and focused position is exhibited in Fig. 4. Similarly in this case also, the degree of mutual interaction between scanning speed and focused position on multiresponse S/N ratio of performance characteristics is more except for the scanning speed at lower level of 1000mm/min

for the focused position -30mm.Hence from the Figs and above results it is evident that the interaction effect is minimal either due to laser power at 750 Watts or focused position at -30mm when the scanning speed is 1000mm/min and 3000mm/min.
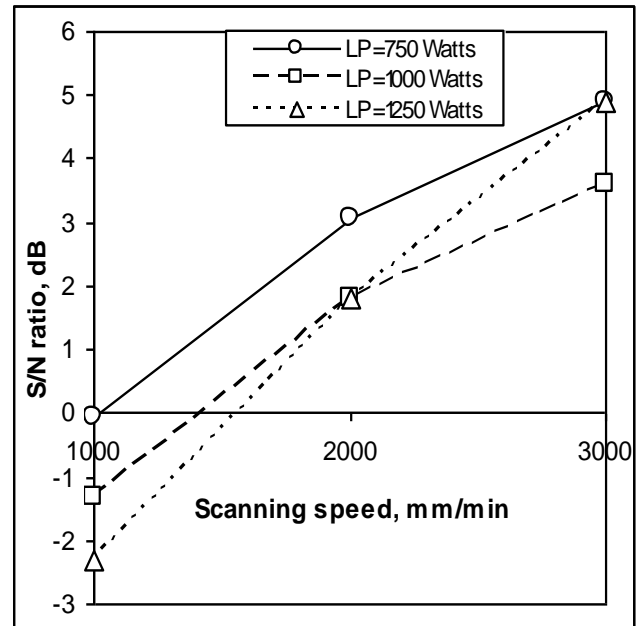

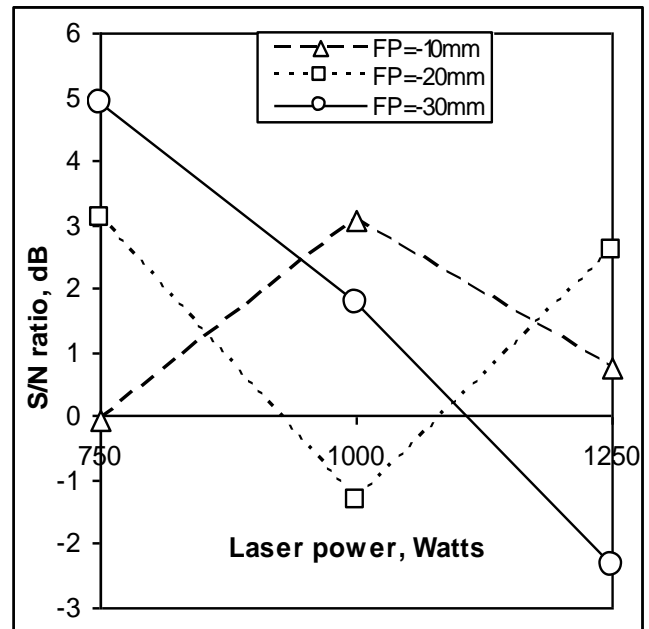**Fig.2.** Interaction effect plot of LP and SS on multiresponse S/N ratio of performance characteristics

Fig.3. Interaction effect plot of LP and FP multiresponse S/N ratio of performance characteristics
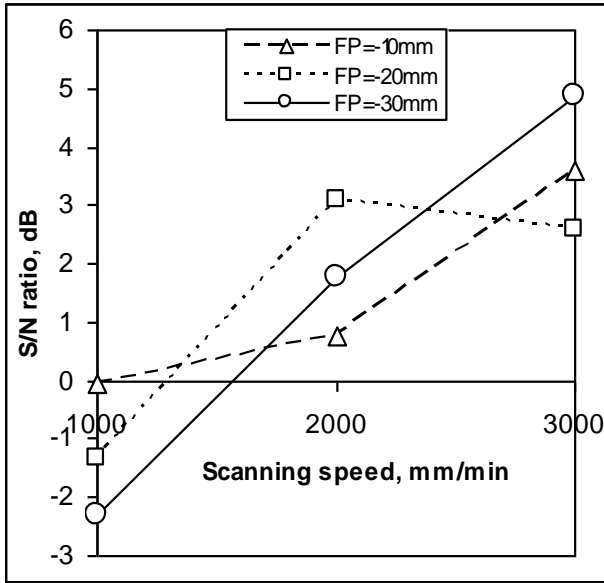
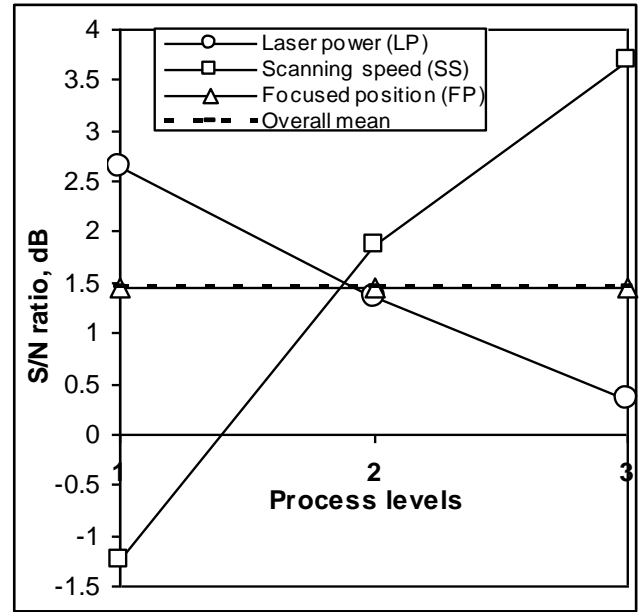**Fig.4.** Interaction effect plot of SS and FP on multiresponse S/N ratio of performance characteristics

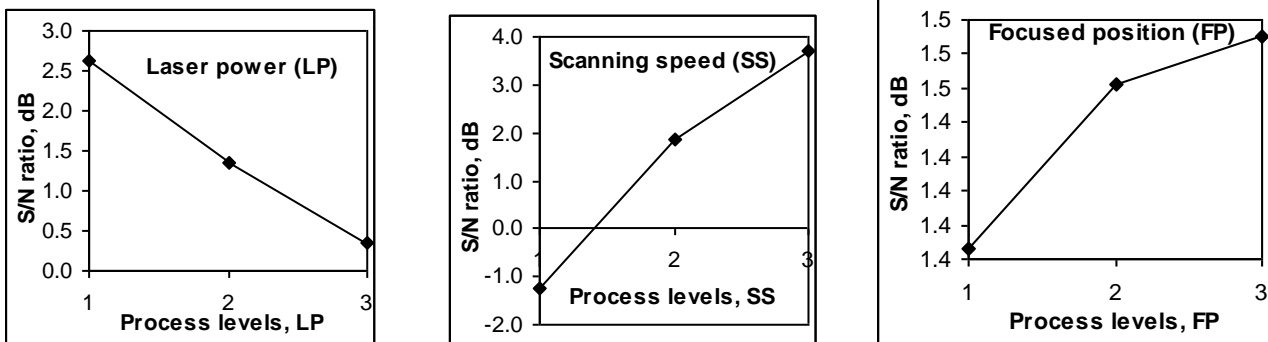**Fig.5.** Response graph of control parameters

Fig. 6. Average values of S/N ratio of each process parameter at each levels 1-3.

Fig.6. shows the Average values of S/N ratio of each process parameter at each level 1-3. The S/N ratio analysis (Fig.4) suggests that the lower level of LP and higher levels of SS and FP are the best optimum levels for achieving the minimum heat input and maximum tensile strength of laser hardened titanium with 1.6mm thickness sheet.

4.2 Analysis of Means

The analysis of means (ANOM) is applied to establish the optimal process parametric settings and it is the process of estimating the main effects of each process parameter [5]. The effect of a parameter level is the deviation it causes from the overall mean response. The overall mean of associated with nine experiments is computed as:

$$m = \frac{1}{9}\sum_{k=1}^{9}\eta_k \tag{9}$$

The effect of a process parameter level i for parameter *j* is:

$$\left(m\right)_{i,j} = \frac{1}{l}\sum_{i=1}^{l}\left(\eta_i\right)_j \tag{10}$$

The optimum level of a process parameter is the level, which gives the highest S/N ratio. The maximization of multiresponse S/N ratio for the optimal level associated with each process parameter is:

$$j_{i,opt} = \max\left\{\left(m\right)_{i,j}\right\} \quad \text{For } j = LP, SS, FP; \ i = 1, 2, 3 \tag{11}$$

The ANOM result for multiresponse S/N ratio characteristics is represented in the response graph as represented in Fig. 5. Thus, for the optimal process parameter setting for the present investigation is LP1, SS3 and FP3. Hence, the best combination values to accomplish the minimum heat input (HI) and maximum tensile strength (σ) are:

- Laser power (LP1): 750 Watts

- Scanning speed (SS3): 3000 mm/min
- Focused position (FP3): -30mm.

However, the relative contribution of each process parameter on multiple performance characteristics is determined through ANOVA that enables more accurate determination of the optimal process parameter levels.

4.3 Analysis of Variance

The ANOVA is a computational technique, which is used to estimate the relative significance of each process parameter in terms of percent contribution on the overall response [5, 6]. The ANOVA is also required for estimating the variance of error for the effects and confidence interval of the prediction error. The ANOVA table contains the degrees of freedom, sum of squares, mean square and percentage contribution. The parameters with higher percentage contribution are ranked higher in terms of importance in the experiment and also have significant effects in controlling the overall response.

Table 4 illustrates the results of ANOVA performed on multiresponse S/N ratio of performance characteristics. Analyzing the measured responses by the Design-expert software, the fit summary output indicates that the linear model is significantly significant for the models laser power and scanning speed `except for the focused position value of "Probability > F" in Table 4 is more than 0.0500. The adequacy of the developed model for multiresponse S/N ratio of performance characteristics were tested using the analysis of variance (ANOVA) technique and the results of the linear response surface model fitting in the form of analysis of variance (ANOVA) are given in Table 4. The test for significance of the regression model, the test for significance on individual model coefficients test was performed using the

same statistical software package. The results from ANOVA are shown in Table 4. F ratio corresponding 95% confidence level in calculation of three process parameters analysed from is accurately is $F_{0.05, 2, 8} = 4.459$. From Table 4, it is apparent that the F-values of factor LP and factor SS, were all greater than $F_{0.05, 2, 8} = 4.459$. And factor FP is not a significant affecting parameter for minimum heat input and maximum tensile strength. F-value of FP (0.807465) is less than $F_{0.05, 2, 8} = 4.459$. Most significant parameter that effect the heat input and tensile strength is scanning speed SS followed by laser power (LP).

The same Table 4 show also the other adequacy measures R^2, adjusted R^2 and predicted R^2. The coefficient of determination R^2 indicates the goodness of fit for the model. In this case, all the values of coefficient of determination R^2 are nearly equal to 1. Clearly, we must have $0 \leq R^2 \leq 1$, with larger values being more desirable. R^2 values for multiresonse S/N ratio is 0.999993. It indicates that the R^2 value is nearly equal to1.The values of "Probability > F" in Table 4 is less than 0.0500 indicate that all model is significantly significant. The Model F-value of 48003.07 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case all laser process parameters LP, SS, FP are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. The "Pred R-Squared" of 0.999859 is totally in reasonable agreement with the "Adj R-Squared" of 0.999972. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable.The adequate precision ratio above 4 indicates adequate model discrimination. In this case the ratio of 653.1637 indicates an adequate signal.

Table 4. ANOVA table for multiresponse S/N ratio linear Model

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F		Percentage contribution
Model	45.17697	6	7.5295	48003.07	< 0.0001	significant	99.99
LP	7.851928	2	3.92596	25029.34	< 0.0001		17.38
SS	37.32479	2	18.6624	118979.1	< 0.0001		82.61
FP	0.000253	2	0.00013	0.807465	0.5533		5.60E-04
Residual	0.000314	2	0.00016				6.95E-04
Corrected Total	45.17728	8					100.00

Std. Dev.	0.01252	R-Squared	0.999993
Mean	1.44799	Adj R-Squared	0.999972
C.V. %	0.86493	Pred R-Squared	0.999859
PRESS	0.00635	Adeq Precision	653.1637

It is clearly observed in ANOVA table that the scanning speed has major contribution (82.61%) in optimizing the multiple performance characteristics followed by laser power (17.38%) and focused position 5.60E-04%. From the table it has been also confirmed that scanning speed is the most influencing factor as compared to the laser power. As SS decreases and LP increases results increase in the heat input and hence decrease in tensile strength. Besides, focused position has no significant effect on heat input as well as on tensile strength.

Therefore, from the results it clear that only two factors scanning speed and laser power played important role in optimizing the heat input and tensile strength. Further, it is also seen that the ANOVA has resulted in around 6.95E-04% of error contribution, indicating that the interaction effects of the process parameters are negligible for simultaneously minimizing the heat input and maximizing tensile strength.

4.4 Verification Test of Optimal Result

Fig. 7 shows the relationship between the computed or actual and predicted values of mutiresponse S/N ratio. The Figure indicates that the developed model is adequate because the residuals in prediction of each response are minimum values, since the residuals tend to be close to the diagonal line. Fig. 8 shows the comparison of computed values with predicted values of multiresponse S/N ratio of performance characteristics. From the Figures it has been observed and ensured that predicted values are very closely agreement with the experimental values.

Table 5. Confirmation of experiments

Trial No	Process parameters			Responses		S/N ratio, dB		
	LP, Watts	SS, mm/min	FP, mm	HI, J/cm	σ, N/mm^2	η_1 forH1	η_2 for σ	Multiresponse η
1	750	3000	-30	150	464	-43.522	53.3304	4.9043
2	750	3000	-30	150	461	-43.522	53.274	4.8761
			Average	150	462.5		Average	4.8902

The verification experiment is the final step in Taguchi design. Since the optimum condition of parameter levels was not included in the main experiment, an indirect method was chosen to predict the multiple characteristics. The predicted optimum value of S/N ratio (η_{opt}) is determined as [5]:

$$\eta_{opt} = m + \sum_{j=1}^{p} \left[\left(m_{i,j} \right)_{max} - m \right] \tag{12}$$

where, $(m_{i,j})_{max}$ is the S/N ratio of optimum level i of parameter and p is the number of main design parameters that affect the multiple performance. The predicted S/N ratio for the optimum laser process parameter levels (LP1, SS3 and FP3) is 4.8899dB.

The validation experiment was conducted according to the optimal process parameter levels (LP1, SS3 and FP3). Two trials were conducted and the corresponding heat input and tensile strength values were measured. Table 5 summarizes the experimental condition, the actual and average experimental values of HI, σ and average value of multiresponse S/N ratio performance. The average value of heat input and tensile strength are 150 J/ cm and 462.5 MPa respectively. The average multiresponse S/N ratio for the confirmation experiment is 4.8902dB.

In order to judge the closeness of observed value of S/N ratio with that of the predicted value, the confidence interval value of η_{opt} for the optimum process parameter level combination at 95% band is determined. The CI is given by [6]:

$$C.I = \pm \sqrt{\left[F_{(1,\nu_e)} \nu_e \left(\frac{1}{\eta_{eff}} + \frac{1}{\eta_{ver}} \right) \right]} \tag{13}$$

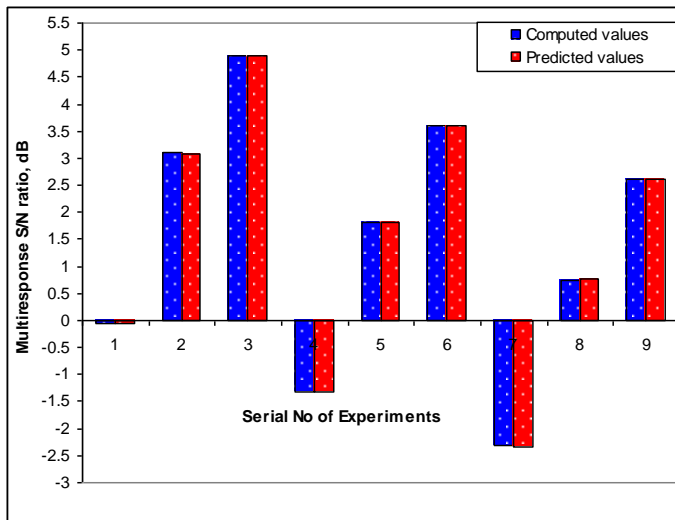where, ν_e is the degrees of freedom for error = 2,

$F_{(1,\nu_e)}$ is the F value for 95% confidence interval = 18.51,

ν_e is the variance of error = Mean square error = 0.00016.
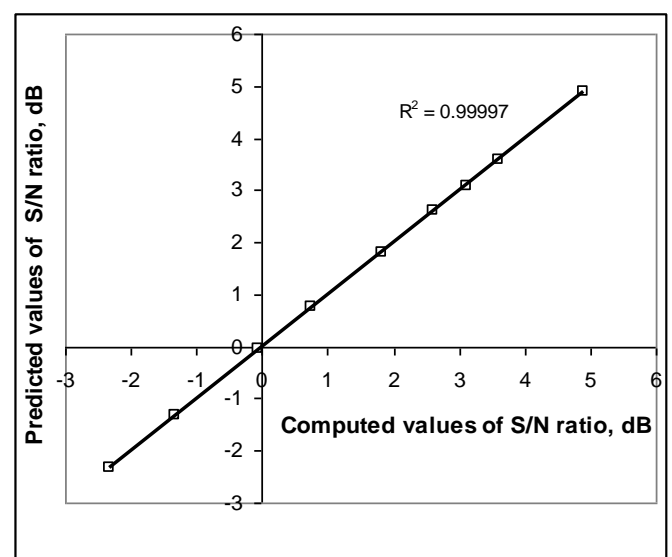
Figure 7. Scatter diagram of multiresponse S/N ratio multiperformance characteristic

Figure 8. Comparison between computed and predicted values of multiresponse S/N ratio characteristics

$$\eta_{ver} = \frac{N}{1 + v} \qquad (14)$$

N = Total trial number of experiments = 9,

v = Degrees of freedom of p process parameters = 6,

η_{ver} is the validation test trial number = 2.

In the present study, the prediction error i.e. the difference between η_{opt} and η_{obs} is 0.00028dB, which is within the CI value of ±0.0609 dB, and hence, justifying the adequacy of the additivity of the model. Thus, the optimal process parameter level combination for simultaneously minimizing the heat input and maximizing tensile strength is LP1 (750Watts), SS3 (3000mm/min) and FP3 (-30mm). Therefore, results revealed the predicted optimal values of tensile strength and heat input of commercially pure titanium sheet produced by laser transformation hardening process are 464 N/mm^2 and 141.667 J/cm, respectively, for the optimized laser process parameters, LP=750 Watts, SS=3000mm/min, and FP=-30mm.

5. CONCLUSIONS

Taguchi approach with utility concept has been successfully used to determine the best combination values of laser process parameters, such as laser power, scanning speed, and focused position for simultaneously minimizing the heat input and maximizing the tensile strength during laser transformation hardening of commercially pure titanium using Nd:YAG laser. The optimal process parameter levels were obtained through ANOM and the percent contribution of each process parameter in optimizing the multiple performances was determined through ANOVA. From the analysis of experimental results using S/N ratio and ANOVA the following conclusions are made from the current investigation within the ranges of the process parameters selected.

- The results of ANOM indicate that a combination of higher levels of scanning speed and focused position along with laser power in the lower level is necessary for simultaneously minimizing the heat input and maximizing the tensile strength.

- The results of ANOVA clearly indicate that the scanning speed and laser power are the most significant parameters followed by focused position in optimizing the multiple performances.

- The ANOVA also resulted in very small value 6.95E-04% of error, indicating that the interaction effects of process parameters on optimization of multiple performances are absolutely negligible.

- The utility concept is found to be very simple and useful for simultaneous optimization of several performance characteristics.

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