



STATISTICAL MODELLING AND OPTIMIZATION OF OPERATING PARAMETERS IN LASER FORMING OF Ti6Al4V ALLOY THIN METAL SHEETS

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ARTICLE INFO

Article History

Received: February 10, 2026

Reviewed: April 17, 2026

Accepted: May 17, 2026

Published: June 30, 2026

Keywords:

Laser forming,
Ti6Al4V alloy thin sheets,
Fiber laser,
ANOVA analysis,
Process control.

ABSTRACT

Laser forming shapes metal sheets into a functional part by exploiting thermally induced stresses rather than mechanical forces. Localized irradiation by a high-power laser generates a steep temperature gradients that drive the deformation of the sheet. Because the processing parameters significantly influence these thermal stresses, understanding their individual and interactive effects is crucial for precise control of deformation. In this paper, the interactions between laser forming parameters and bending angle are investigated using a statistical approach. Experiments were performed using a 4 kW fiber laser on thin Ti6Al4V alloy sheets. Based on the experimental data, a correlation between the bending angle and process parameters was established using a second-order regression model. An R^2 value of 96.42% indicates that the proposed equation accurately predicts the bending angle for the defined range of input parameters. Both ANOVA and Pareto analysis demonstrated that the interactive effects of process parameters strongly influence the bending angle. Among the individual factors, scanning speed was identified as the most influential parameter, followed by the number of scans, laser power, and beam size. The optimization of processing parameters suggest a laser power of 300 W, a scan speed of 2000 mm/min, a beam size of 2 mm, and 10 scans can produce a maximum bending angle of 32°.



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I. INTRODUCTION

The application of high-strength, lightweight materials has increased in the automotive, aerospace, and battery electric vehicles (BEV) sectors. However, many of these materials exhibit poor formability at room temperature, which limits their processing using conventional mechanical forming methods [1]. To overcome this challenge, laser forming has emerged as an effective alternative. In this process, controlled thermal stresses generated by localized laser heating deform the metal component, as illustrated in Figure 1, without any physical contact or dedicated tooling. Therefore, it can shape a range of materials, including steels, aluminium and magnesium alloys, and composites, while exhibiting significantly lower spring-back compared to traditional forming processes [2]. This makes the technique particularly attractive for applications that demand high precision and flexibility. As a result, laser forming has been adopted in several industries, such as aerospace, automotive, shipbuilding, and microelectronics. It is commonly employed for rapid prototyping, fabrication of customized three-dimensional components like aircraft panels and ship hull sections, production of biomedical implants, two-dimensional bending of sheets, plates, rods, tubes, and wires, as well as for straightening profiles, correcting distortions, and fine adjustment of micro-scale components in MEMS devices [3]. Despite these advantages, laser forming is not a straightforward process, as the resulting deformation depends on the combined influence of several interrelated parameters. These include laser characteristics such as power density, wavelength, beam size and shape, and surface absorption behavior; geometric factors like sheet thickness and length; and material properties including thermal expansion coefficient, yield strength, and thermal conductivity [4]. The selection of these parameters is important for defining the physical bending phenomenon. Over the past three decades, researchers have attempted analytical formulations, numerical simulations, and statistical techniques to understand how laser-forming parameters influence the resulting bending angle.

For the given sheet thickness and input energy parameters, Geiger and Vollertsen [5] employed heat balance principles to derive the thermal profiles generated along the sheet thickness responsible for the bending angle and direction. Out of these, temperature gradient-based profiles were widely studied. According to the temperature gradient phenomenon, when thick sheets are irradiated with a high scanning speed and a small laser spot, a steep temperature gradient develops through the thickness. This gradient generates non-uniform thermal strains and stresses, forcing the sheet to bend toward the region experiencing maximum compressive strain. In contrast, thin sheets exposed to a small beam diameter and slow scanning speed tend to develop a nearly uniform temperature field, leading to the buckling of the sheet. The sheet shrinkage phenomenon becomes dominant when the laser spot size exceeds the sheet thickness, producing a more uniform stress distribution that drives deformation. Although these bending mechanisms provide valuable insights, the underlying analytical formulations rely on simplifying assumptions, which limit their predictive accuracy. To overcome these limitations, researchers have also developed numerical models using finite element and finite element analysis (FEM/FEA) techniques [6]. The coupled thermo-mechanical phenomenon of the process was modelled using the FEM approach and simulated for various process conditions to identify the suitable process window. In parallel, statistical approaches ranging from classical regression to soft computing methods have emerged as fast and cost-effective tools capable of predicting bending angles in real time.

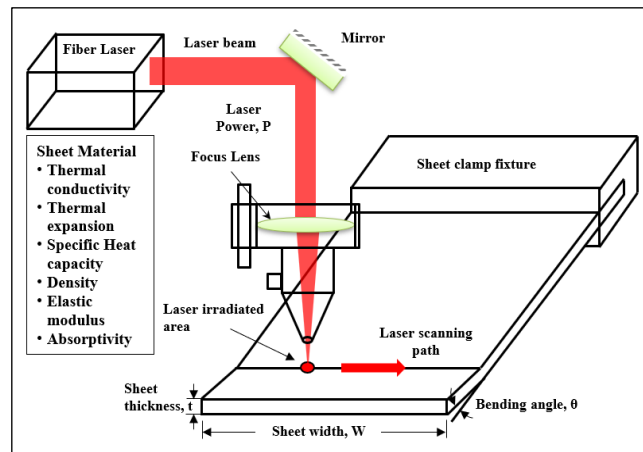


Figure 1: Deformation behaviour of the sheets under the temperature gradient mechanism.
Source: Authors, (2026).

While theoretical and numerical modeling addressed through-thickness thermal behavior, experimental modeling focused on the individual effects of process parameters on the bending angle. Among these parameters, laser power is generally reported to have a direct effect on bending behavior, with the bend angle increasing proportionally as the laser power is raised within an effective operating range. When the applied power falls below a critical threshold, permanent deformation does not occur, as elastic recovery becomes dominant. Therefore, careful selection of laser power is crucial to ensure sufficient plastic deformation while avoiding undesirable effects such as surface melting or purely elastic bending [7–11]. In contrast, laser scanning speed exhibits an inverse relationship with the bend angle. Higher scanning speeds reduce the energy input per unit length, leading to smaller bending angles. Vollertsen [12] quantitatively described this dependency, showing that the bend angle (θ) varies with scanning speed according to $\theta \propto V^{-0.63}$ for steel and $\theta \propto V^{-0.54}$ for aluminium. Several studies have further examined the combined influence of laser power and scanning speed and consistently reported a reduction in bend angle with increasing scanning speed [13], [14]. In addition to laser parameters, geometric factors significantly affect laser forming behavior. Sheet thickness, in particular, has been shown to have a strong inverse correlation with the bend angle, as thicker sheets require greater thermal input to achieve comparable deformation [15].

With respect to sheet width, [16] observed a slight drop in the bend angle as width increased, whereas [17] reported the opposite trend for Ti-6Al-4V alloy sheets. Sheet length likewise affects deformation: experiments by [18] indicate that longer sheets undergo smaller bending angles because greater length promotes more heat dissipation. Finally, the deformation achieved in a single laser pass is typically small, necessitating multiple scans to reach the desired bend angle. However, repeated scanning along the same line reduces the temperature gradient due to accumulated thermal stresses, which in turn diminishes the achievable bend angle and restricts the applicability of the process to larger-scale operations [19], [20]. It is evident from the above discussion that the efforts made to define the relationship between the processing parameters and bending angle were limited to independent parameters. Additionally, these reported studies focused on thick sheets of ductile materials, such as steel and its alloys. However, for successful industrial implementation of laser forming, a comprehensive understanding of how operating parameters collectively influence the bending angle is essential. In the present work, a statistical framework is employed to investigate the effect of independent and derived processing parameters on the bending angle using a statistical approach. The study specifically focuses on laser forming of thin sheets of high-strength Ti-6Al-4V alloy, a material of significant industrial relevance but limited formability at room temperature. Further, the critical and optimized processing parameters range was determined based on the ANOVA analysis and the propagation of error approach.

II. EXPERIMENTS

Figure 2 shows a 4 kW CW-operated fiber laser machine used for conducting the process trials on Ti6Al4V alloy metal sheets. The experimental setup includes the sheet holding unit wherein a C-clamp fixture was used to hold the sheet from one side, while the opposite end was left free, thereby establishing cantilever boundary conditions. The temperature monitoring unit comprises a S-type thermocouple for monitoring the temperature change during the process. For bend angle measurement, a digital protractor was used, and the measurements were taken offline.

The experiments were designed using the full factorial approach, wherein four parameters were varied in three levels as shown in Table 1. The experimental design of 3^4 combinations corresponds to a total of 81 experimental runs. During the process, a laser beam was moved along the width of the sheet, perpendicular to its length, in both forward and reverse directions. One complete pass of the laser beam across the sheet width was defined as a single scan. Upon completion of all trials, the resulting bending angles were measured and subsequently analyzed using a regression-based statistical approach.

Table 1: Range of process parameters.

Input Variable	Parameters	Unit	Min. Value	Mid Value	Max. Value
Laser power (P)	Main	Watt	200	250	300
Scanning speed (V)	Main	mm/min	2000	3000	4000
Beam size (D)	Main	mm	1	1.5	2
Number of scans (NS)	Main	-	5	10	15

Source: Authors, (2026).

III. STATISTICAL MODELLING

Figure 3 presents the overall methodology followed for developing the regression model and performing the analysis. The bending angle measurements obtained from the experiments were first organised into main and derived parameter sets. These datasets were then used to train the regression model. Out of the 81 experimental observations, 70% were allocated for model training, while the remaining 30% were reserved for validation. All analyses were carried out using Minitab 21. Using the trained dataset, a second-order quadratic regression equation was formulated. This equation defines the quantitative relationship between the bending angle (BA) and the key laser-processing parameters: laser power (P), scan speed (V), beam diameter (D), number of scans (NS), and energy density (ED). The model incorporates linear, quadratic, and interaction terms to capture both individual and combined effects of these variables on the bending angle. Equation 1 summarizes this relationship by expressing the bending angle as a function of the main and derived parameters.

$$\text{Bending Angle (BA) in degrees} = -17.4 + 0.0416 P \text{ (W)} + 0.00822 V \text{ (mm/min)} + 1.29 D \text{ (mm)} + 0.837 NS - 0.000023 P \text{ (W)} * V \text{ (mm/min)} + 0.0155 P \text{ (W)} * D \text{ (mm)} + 0.01176 P \text{ (W)} * NS - 0.001718 V \text{ (mm/min)} * D \text{ (mm)} - 0.000758 V \text{ (mm/min)} * NS + 0.059 D \text{ (mm)} * NS \text{ (1)}$$

IV. RESULTS AND DISCUSSION

This section discusses the performance of the proposed regression equation by comparing the test and validation model results. It is followed by ANOVA analysis and interactive parametric analysis based on the contour plots. Subsequently, the response optimization results are presented and discussed to identify the optimal parameter combinations. Finally, the predictive capability of the proposed regression model is evaluated through experimental validation.

IV.1 MODEL VALIDATION

Table 2 shows that the regression model exhibits a strong fit to the experimental data, with an R^2 value of 95.11%, indicating that 95.11% of the variation in the response (bend angle or deformation) is explained by the model. The adjusted R^2 (94.05%) accounts for the number of predictors, confirming that most included terms contribute meaningfully to model performance. The predicted R^2 (92.33%) is close to the adjusted R^2 , suggesting good predictive capability and minimal over-fitting. The standard deviation ($S = 2.13857$) reflects a low level of residual error, reinforcing the model's reliability.

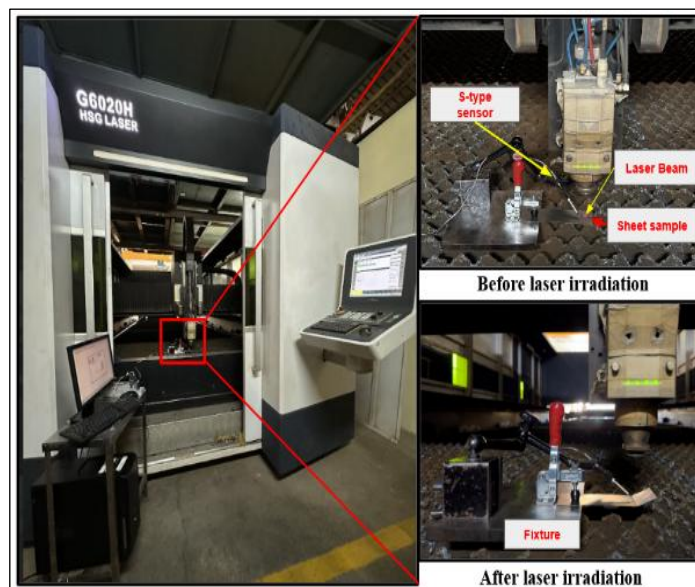


Figure 2: A fibre laser machine is used for the laser forming of Ti6Al4V alloy sheet.

Source: Authors, (2026).

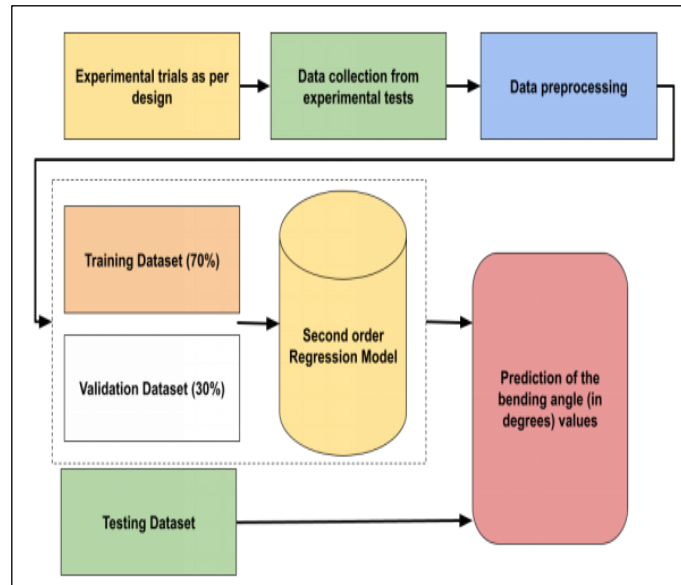


Figure 3: Framework for regression model.

Source: Authors, (2026).

Table 2: Regression model accuracy.

Std. Deviation	R-square	R-square (adjusted)	R-square (predicted)
2.13857	95.11%	94.05%	92.33%

Source: Authors, (2026).

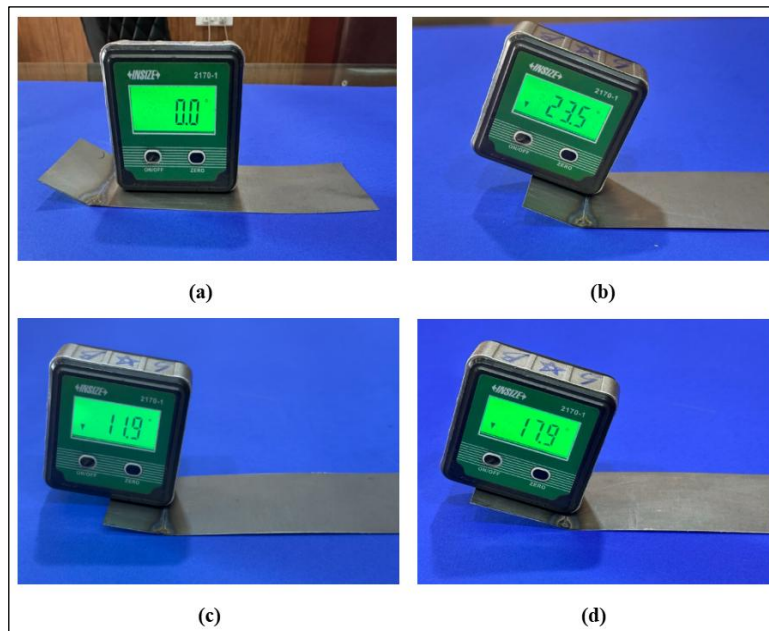


Figure 4: Bend angle measurement **(a)** angle gauge set to zero **(b)** bend angle measurement (Sample No.23: P=300W, V=3000 mm/min, D=1.5 mm, N=15) **(c)** bend angle measurement (Sample No.5: P=200W, V=4000 mm/min, D=2 mm, N=20) **(d)** bend angle measurement (Sample No.22: P=250W, V=2000 mm/min, D=1 mm, N=15).

Source: Authors, (2026).

IV.2 ANOVA ANALYSIS

Table 4 shows the ANOVA analysis of the experimental test results data. The ANOVA results show that the developed regression model is statistically significant ($F = 89.45$, $p < 0.001$), indicating that the selected process parameters collectively explain a large portion of the variation in the bend angle. Among the individual factors, scanning speed (V) is the only parameter that shows a statistically significant effect ($p = 0.004$), suggesting that speed changes have a noticeable influence on the bending response. In contrast, power (P), beam size (D), and number of scans (NS) do not show significant individual effects within the studied range. However, several interaction effects are found to be important. The interactions between power and number of scans ($P \times NS$) and between speed and number of scans ($V \times NS$) are highly significant ($p < 0.001$), indicating that the bending behavior is strongly affected when these parameters change together.

The interaction between power and speed ($P \times V$) is also significant ($p = 0.007$), highlighting the combined influence of these two parameters on the process. Additionally, the interaction between speed and beam size ($V \times D$) shows a near-significant effect ($p = 0.052$), suggesting a possible influence under certain conditions.

Table 3: Analysis of Variance (ANOVA) analysis.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	10	4091.08	409.108	89.45	0
P (W)	1	6.1	6.1	1.33	0.254
V (mm/min)	1	41.01	41.014	8.97	0.004
D (mm)	1	0.31	0.312	0.07	0.795
NS	1	8.86	8.863	1.94	0.171
P (W)*V (mm/min)	1	35.95	35.945	7.86	0.007
P (W)*D (mm)	1	4.1	4.097	0.9	0.349
P (W)*NS	1	186.66	186.659	40.81	0
V (mm/min)*D (mm)	1	18.14	18.142	3.97	0.052
V (mm/min)*NS	1	298.58	298.585	65.29	0
D (mm)*NS	1	0.48	0.478	0.1	0.748
Error	46	210.38	4.573		
Total	56	4301.46			

Source: Authors, (2026).

IV.3 EFFECT OF PROCESS PARAMETERS

Figure 5 illustrates the contour plots depicting the variation of the bending angle with processing parameters. It can be seen in contour plot 4 (a) that higher laser power combined with lower scanning speed results in a larger bending angle, mainly because more heat is delivered to the sheet and retained for a longer interaction time. As the scanning speed increases, the bending angle drops, indicating reduced heat input and weaker thermal gradients. A similar trend is observed in the contour plot 4 (b). Smaller beam diameters produce higher bending angles due to greater energy concentration at the laser spot. Figure 4 (c) shows that the higher bending angle can be obtained with repeated scans at lower scanning speeds. With an increase in the number of scans, the bending angle gradually increases, likely because repeated heating improves the effective temperature gradient needed for further deformation. Similarly, higher scanning speeds provide less interaction time, which lowers the overall thermal input and results in smaller bending angles. Figure 4(d) shows the plot of bending angle versus energy density and scanning speed. At moderate energy densities, combined with slower scanning speeds, tend to produce higher bending angles. However, when the energy density becomes too high or when the scanning speed increases, the bending angle decreases. This suggests that both underheating and overheating can limit the efficiency of the laser forming process.

IV.4 MULTIPLE RESPONSE OPTIMIZATION

Multiple-response optimization was carried out on all 81 experimental runs to determine the most favourable combination of laser processing parameters for maximizing the bending angle (BA) during laser forming. Figure 7 shows the optimized operating parameters during the laser forming of Ti6Al4V alloy metal sheet. The optimization goal for the response was set to maximize BA, with a lower limit of 0.368° and an upper limit of 33.44° . Equal weight and importance (both set to 1) were assigned, indicating that the optimization primarily focused on achieving the highest possible bending angle without prioritizing other secondary objectives. At these parameter settings, the predicted bending angle (BA) is 33.44° . The standard error of the fitted value (SE Fit) is 1.19, which indicates a reasonably good precision of prediction. The 95% confidence interval (CI) for the mean response ranges from 31.30° to 36.04° , suggesting that if the experiment is repeated under similar conditions, the mean bending angle would likely fall within this interval. Furthermore, the 95% prediction interval (PI) spans from 29.44° to 37.89° , representing the range within which individual future observations are expected to occur. Overall, the optimization results demonstrate a strong correlation between laser parameters and bending response, with the predicted model providing a reliable estimate of the bending angle under the optimal conditions.

Table 4: Analysis of optimization model results.

Parameters				
Response	Fit	SE Fit	95% CI	95% PI
BA (Degrees)	33.44	1.19	(31.30, 36.04)	(29.44, 37.89)

Source: Authors, (2026).

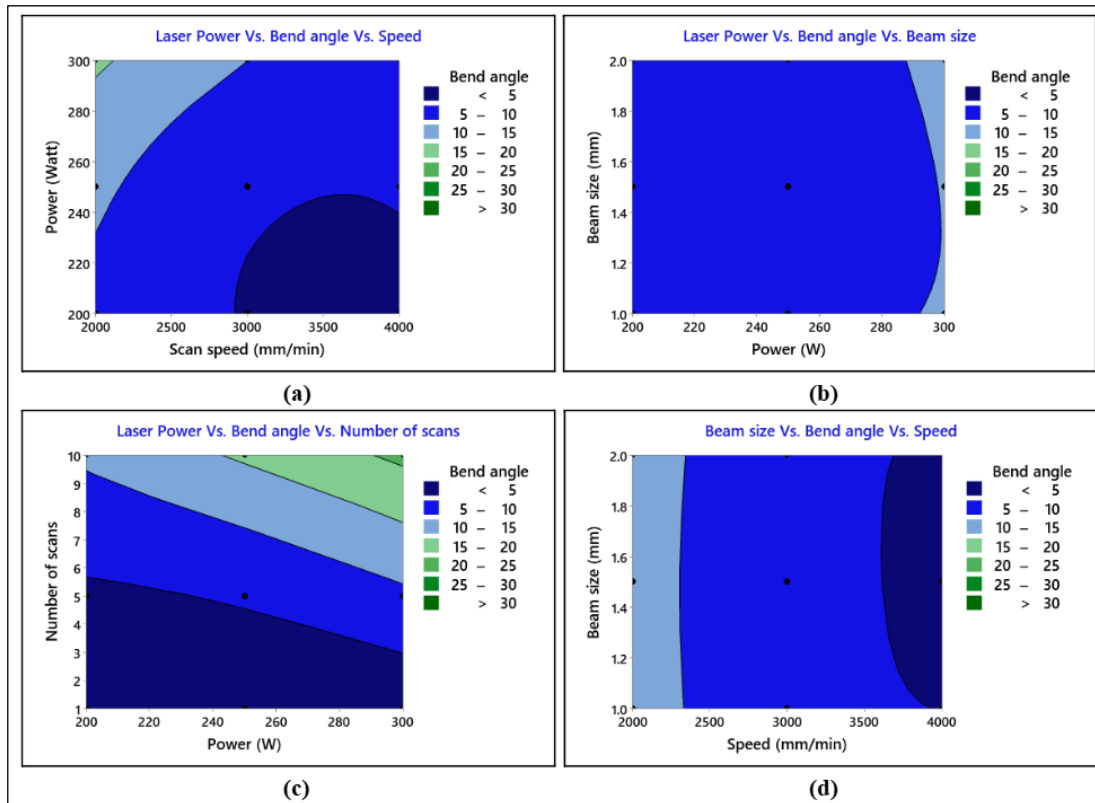


Figure 5: Contour plots showing the interactive effects among processing parameters on the bending angle of Ti6Al4V alloy metal sheet. Source: Authors, (2026).

Table 5: Response optimization results.

Parameters						
Response	Goal	Lower	Target	Upper	Weight	Importance
BA (Degrees)	Maximum	0.368	33.44	-	1	1

Source: Authors, (2026).

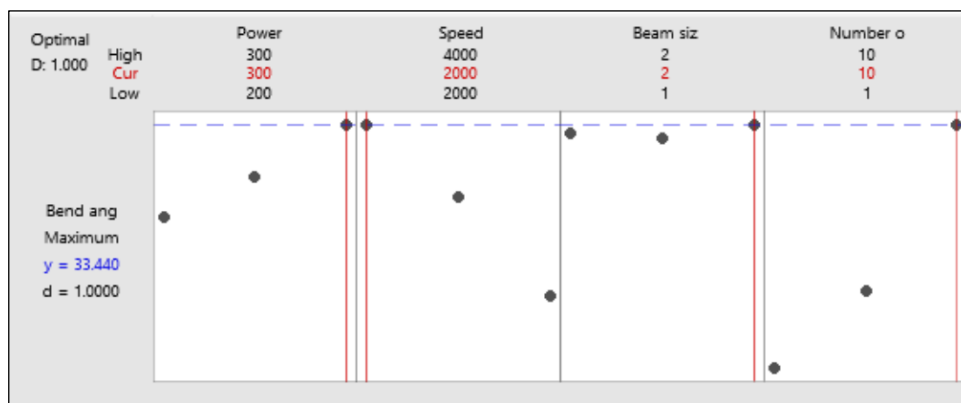


Figure 6: Effect of optimized processing parameters on the bend angle. Source: Authors, (2026).

V. CONCLUSIONS

A detailed process optimization study was performed through extensive experimental work and statistical modelling. A second-order quadratic mathematical expression for predicting the bending angle of the Ti6Al4V alloy thin metal sheet of thickness 0.4 mm was derived using the statistical regression approach. A full factorial experimental process trials were performed on the Ti6Al4V alloy metal sheets using the continuous wave fiber laser with varying laser power, scan speed, beam size, and number of scans. Using the experimental results data as input for the regression model, the bending angle of the sheet was predicted. The prediction accuracy of the regression model was verified by comparing the bending angle results predicted by the model with the experimental bending angle results. The major findings from these studies are given below.

- The regression model demonstrates a strong fit to the experimental data, with an R^2 value of 95.11%, indicating 95.11% of the variation in the response (bending angle).
- The Error mean square (2.13857) is low, showing minimal unexplained variation, and confirms good model adequacy.

- Optimization studies indicate a Power of 300 W, a Speed of 2000 mm/min, a Beam size of 1 mm, with 10 scans giving the maximum bend angle.

Although the regression model yields better predictive performance for the present dataset, it is developed exclusively for Ti-6Al-4V sheets and omits explicit terms for material thermal/mechanical properties. Future studies should extend the dataset to other materials and include relevant material property descriptors to improve model generalizability and physical interpretability.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Vikram Aher.

Methodology: Vikram Aher.

Investigation: Vikram Aher.

Discussion of results: Vikram Aher, Ravindra Navthar.

Writing – Original Draft: Vikram Aher.

Writing – Review and Editing: Vikram Aher, Ravindra Navthar.

Resources: Vikram Aher.

Supervision: Ravindra Navthar.

Approval of the final text: Ravindra Navthar.

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