



 Research Article

Study of The Effect of Laser Cutting Parameters on The Dimensional Accuracy of Inter-Saw Spacer Belts for A Fiber Separator

Journal Website:
<http://sciencebring.com/index.php/ijasr>

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Submission Date: July 20, 2026, **Accepted Date:** August 16, 2026,

Published Date: September 11, 2026

Crossref doi: <https://doi.org/10.37547/ijasr-06-09-04>

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ABSTRACT

The article presents the results of an experimental study of the influence of laser cutting parameters on the dimensional accuracy of an inter-saw spacer belt for a fiber separator. The study was aimed at determining the effect of cutting height and cutting speed on the thickness of the belt blank manufactured from sheet steel using laser technology. A second-order orthogonal experimental design was applied to investigate the relationship between the controlled factors and the resulting dimensional parameter. The experiments were performed using a Bodor A3 2000W MAX CNC laser cutting machine on 1.5 mm thick steel sheet. Cutting height was varied from 0.6 to 0.8 mm, while cutting speed was varied from 7000 to 8000 mm/min. Five repeated measurements were performed for each experimental condition using a 0–25 mm micrometer. Statistical processing of the experimental data demonstrated the repeatability of the experiments and confirmed the adequacy of the obtained regression model according to the Fisher criterion. The analysis showed that the belt thickness varied from 17.697 to 18.230 mm depending on the cutting conditions. The maximum belt width of 18.23 mm was obtained at a cutting speed of 7000 mm/min and a cutting height of 0.7 mm. The obtained results can be used to select appropriate laser cutting parameters for manufacturing inter-saw spacer belts with improved dimensional accuracy.

KEYWORDS

Fiber separator, inter-saw spacer, spacer belt, laser cutting, sheet steel, cutting height, cutting speed, dimensional accuracy, experimental design, regression model.



INTRODUCTION

Inter-saw spacers are important structural elements of saw cylinders used in cotton-processing and fiber separators machines. Their dimensional accuracy directly affects the relative positioning of the saws and other working elements of the saw cylinder. Therefore, deviations in the dimensions of spacer components may negatively influence assembly accuracy, operating stability and the service performance of the machine [1, 2].

The use of steel sheet for manufacturing inter-saw spacer components provides a number of potential advantages, including increased strength and reduced susceptibility to permanent deformation compared with conventional aluminum components. However, the transition to a steel construction requires the development of an appropriate manufacturing technology capable of ensuring the required dimensional accuracy.

Laser cutting is a promising technology for manufacturing such components because it allows complex contours to be produced directly from sheet material without extensive mechanical machining. At the same time, the dimensional accuracy of laser-cut parts depends on the selected processing conditions. Among the technological parameters, the distance between the laser focusing system and the workpiece surface and the cutting speed have a significant influence on the resulting dimensions [3].

The previous analysis presented in the research material indicates that cutting height and cutting speed are the principal factors affecting the dimensions of the inter-saw spacer belt. Therefore, experimental determination of their

optimal combination is necessary to obtain a belt blank with the required dimensions.

The purpose of this study is to determine the influence of laser cutting height and cutting speed on the thickness of an inter-saw spacer belt blank and to establish appropriate processing conditions for its manufacture.

The objective of the research is to experimentally investigate the effect of the two selected laser cutting parameters, develop a mathematical model describing their influence on the resulting dimension, and determine the processing conditions that provide the required dimensional characteristics.

METHODS

Through the planning of the experiment, the study is carried out in a purposeful manner: the required number of trials and the conditions for conducting them are established, which makes it possible to solve the stated scientific problem with the required accuracy [4].

The results of a preliminary analysis showed that, in laser technology, the main factors affecting the thickness of the inter-saw spacer belt blank are the cutting height and the cutting speed [5].

Thus, in the present study the following controllable factors were selected:

X_1 — cutting height, mm;

X_2 — cutting speed, m/min.

The power-density range and the pulse duration of the laser radiation were taken as controlled (constant) factors.

Table 1 gives the levels of the input (independent) parameters selected for the experiment:

Table 1

Factors	-1	0	+1
Cutting height X_1 , mm	0.6	0.7	0.8
Cutting speed X_2 , mm/min	7000	7500	8000

Using these parameters, the experimental conditions are studied in various combinations, and on this basis the most favorable conditions for preparing the inter-saw spacer belt blank by laser cutting are determined.

To determine the influence of the main factors — X_1 (cutting height) and X_2 (cutting speed) — a second-order orthogonal design matrix for a two-factor process is used. This matrix was chosen

because a simple linear mathematical model cannot adequately represent the process under study. For this reason, the analysis is carried out on the basis of a more complex, second-order model.

Below is the second-order orthogonal design matrix, together with the conditions for conducting the experiment:

Table 2

№	X_0	X_1	X_2	$X_1 \cdot X_2$	$(X_1')^2$	$(X_2')^2$	Working matrix Cutting height X_1 , mm	Working matrix Cutting speed X_2 , mm/min
1	+	+	+	+	0.33	0.33	0.8	8000
2	+	-	+	-	0.33	0.33	0.6	8000
3	+	+	-	-	0.33	0.33	0.8	7000
4	+	-	-	+	0.33	0.33	0.6	7000
5	+	-	0	0	0.33	-0.67	0.6	7500
6	+	+	0	0	0.33	-0.67	0.8	7500
7	+	0	-	0	-0.67	0.33	0.7	7000
8	+	0	+	0	-0.67	0.33	0.7	8000
9	+	0	0	0	-0.67	-0.67	0.7	7500

Experiment design matrix

On the basis of this design, the experiments carried out make it possible to determine the optimal conditions for laser cutting and the degree of influence of the factors involved. This,

in turn, serves to increase the accuracy and efficiency of manufacturing the inter-saw spacer belt.

In order to obtain reliable scientific results, the experiment was carried out by cutting a steel sheet 1.5 mm thick.

The experiment was performed on a Bodor A3 2000W MAX CNC laser machine designed for metal cutting [6]. The cutting process was organized according to the following parameters: Cutting height: 0.6 mm, 0.7 mm and 0.8 mm; Cutting speed: 7000 mm/min, 7500 mm/min and 8000 mm/min.

The experiment was carried out in the following sequence:

1. A drawing of the inter-saw spacer belt blank was prepared (Fig. 1);
2. The 1.5 mm thick steel sheet and the finished drawing (file) were loaded into the laser machine's computer;
3. The cutting process was started;
4. The finished samples were separated, and the belt dimensions were precisely measured with a micrometer (0–25 mm) [7].

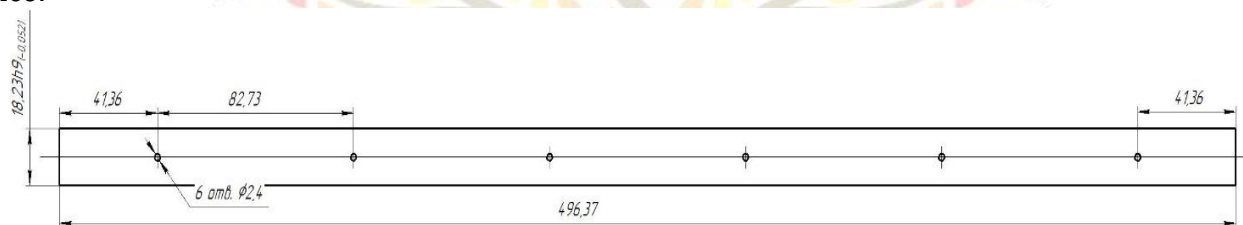


Fig. 1. Drawing of the inter-saw spacer belt of a saw-type fiber separator

This experiment is aimed at determining the optimal conditions for manufacturing the inter-saw spacer belt blank with high accuracy by means of laser technology.

The research work was carried out at “Qishloq xo‘jalik mashinalari” LLC, on a Bodor A3 2000W MAX CNC machine designed for laser cutting of metal (Fig. 2).



Fig. 2. Bodor A3 2000W MAX CNC laser machine for metal cutting

RESULTS AND DISCUSSION

The experiments were carried out on the basis of the theoretical design, with each condition repeated 5 times. The results obtained are given in Tables 3 and 4, respectively.

This table gives the measured thickness values (y_1 – y_5) of the inter-saw spacer belt obtained under each experimental condition. The average values calculated from them form the basis for the subsequent mathematical analysis.

The experiments serve to study the effect of cutting height and cutting speed on the belt thickness. Based on this data, the statistical analysis of the experimental results is given in Table 4.

This approach makes it possible to ensure statistical reliability, as well as to determine the

optimal values of the parameters that affect the cutting process.

In accordance with the requirements of orthogonal design [4], the experiments were repeated several times while varying the ranges of cutting height and cutting speed. This makes it possible to determine how the dimensions of the inter-saw spacer belt of the saw-type fiber separator change.

The results of these experiments are given in Table 3; they make it possible to evaluate the effect of the cutting parameters on the dimensions of the final product.

Taking the confidence level as $R = 0.95$, the variance of the experimental errors used to evaluate measurement accuracy is determined from the following formula:

$$\sigma^2 = S^2 = \frac{1}{n-1} \sum_{i=1}^n (y_i - \bar{y})^2 \quad (1)$$

$\bar{y} = \frac{1}{n} \sum_{i=1}^n y_i$ — the arithmetic mean value of the measurement results. When the degree of accuracy is unknown, the confidence estimate in point estimation takes the following form:

$$|a - \bar{y}| < t(P; k) \frac{S}{\sqrt{n}} \quad (2)$$

Here the coefficient $t(P; k)$ depends not only on the confidence probability (P) but also on the number of measurements n . Here:

a — the true value of the parameter being measured, which is to be found,

k — the number of degrees of freedom (usually $k = n - 1$).

The symmetric confidence estimate is expressed as follows:

$$(\bar{y} - \varepsilon) < a < (\bar{y} + \varepsilon) \quad (3)$$

where ε is the measurement error.

For example: for a cutting height of $X_1 = 0.8$ mm and a cutting speed of $X_2 = 7000$ mm/min, the results of five repeated measurements were as follows: $y_1 = 17.720$ mm; $y_2 = 17.874$ mm; $y_3 = 17.978$ mm; $y_4 = 18.028$ mm; $y_5 = 17.771$ mm. To evaluate the measurement accuracy at a confidence level of 0.95, the arithmetic mean value of $\bar{y}$ is determined as follows:

$$\bar{y} = \frac{1}{5} (17.720 + 17.874 + 17.978 + 18.028 + 17.771) = 17.874 \text{ mm}$$

and we determine the empirical variance:

$$S = \sqrt{\frac{1}{n-1} [(y_1 - \bar{y})^2 + (y_2 - \bar{y})^2 + (y_3 - \bar{y})^2 + (y_4 - \bar{y})^2 + (y_5 - \bar{y})^2]} = 0.131 \quad (4)$$

According to Student's distribution, for $P = 0.95$, $k = 4$, $t = t(P; k) = 2.776$. The error of the arithmetic mean is then equal to:

$$\varepsilon = t(P; k) \frac{s}{\sqrt{n}} = 2.776 \frac{0.04832}{\sqrt{5}} = 0.1627 \quad (5)$$

For the symmetric confidence estimate:

$$(17.874 - 0.1627) < a < (17.874 + 0.1627), \text{ or } 17.711 < a < 18.037 \quad (6)$$

Thus, the true value of the parameter being measured (belt thickness) lies within the interval from 17.711 to 18.037. According to the analysis, all the obtained measurement results lie within the 0.95 confidence interval.

The reliability of all the remaining trials is determined in the same way. The error variances are given in Table 4.

The homogeneity of the variances is checked by means of the Fisher criterion.

$$F_{calc} = \frac{S_{max}^2}{S_{min}^2} = \frac{S_4^2}{S_1^2} = \frac{0.01723}{0.01708} = 1.0088 \quad (7)$$

The tabulated value of the Fisher criterion, for the maximum variance with $f = 5$ and the minimum variance with $f = 5$, is $F_{tab} = 5.05$.

Thus, all the variances are homogeneous, and the experiment conducted possesses the property of reproducibility. As the mathematical model for the indicator under study, we now select a second-order polynomial of the form:

$$y = b_0 + b_1x_1 + b_2x_2 + b_{12}x_1x_2 + b_{11}x_1^2 + b_{22}x_2^2 \quad (8)$$

Based on the following formulas, the coefficients $b_0, b_1, b_2, b_{12}, b_{11}, b_{22}$ are determined respectively:

$$b_0 = b_0' - b_{11}x_1^2 - b_{22}x_2^2 \quad (9)$$

$$b_i = \frac{\sum_{u=1}^6 x_{iu} \cdot \bar{y}}{6} \quad (10)$$

$$b_{ij} = \frac{\sum_{u=1}^4 x_{iu} \cdot x_{ju} \cdot \bar{y}}{4} \quad (11)$$

$$b_{ii} = \frac{\sum_{u=1}^9 (x'_{iu})^2 \cdot \bar{y}}{9} \quad (12)$$

Substituting the corresponding values from Table 4 into formulas (3.10)–(3.13), the coefficients are determined. Substituting the values found into regression equation (3.9), we obtain the regression equation in the following form:

$$y = 18.2301 - 0.0095 \cdot x_1 - 0.0062 \cdot x_2 + 0.0111 \cdot x_1 \cdot x_2 - 0.2483 \cdot x_1^2 - 0.2705 \cdot x_2^2 \quad (13)$$

We now assess the significance of the coefficients of regression equation (3.14). To do this, we first determine the reproducibility variance of the experimental results:

$$S_{rep}^2 = \frac{S_1^2 \cdot f_1 + S_2^2 \cdot f_2 + \dots + S_9^2 \cdot f_9}{f_1 + f_2 + \dots + f_9} = \frac{5 \cdot 0.155}{45} = 0.01717 \quad (14)$$

For the case $K = 0$, based on [4], the variance of the regression-coefficient errors is determined by the following formula:

$$S_{b_i}^2 = \frac{S_{rep}^2}{\sum_1^N x_{iu}^2} \quad (15)$$

$$\begin{aligned}
 S_{b_0}^2 &= \frac{0.01717}{9} = 0.00191; \\
 S_{b_1}^2 &= S_{b_2}^2 = \frac{0.01717}{6} = 0.00286; \\
 S_{b_{11}}^2 &= S_{b_{22}}^2 = \frac{0.01717}{2} = 0.00858; \\
 S_{b_{12}}^2 &= \frac{0.01717}{4} = 0.004292.
 \end{aligned} \tag{16}$$

The squared errors (i.e., the squares of the standard deviations) are calculated from the following formula:

$$\begin{aligned}
 S_{b_0} &= 0.04368; \\
 S_{b_1} &= S_{b_2} = 0.05349; \\
 S_{b_{12}} &= 0.06552; \\
 S_{b_{11}} &= S_{b_{22}} = 0.09266.
 \end{aligned} \tag{17}$$

The error in estimating the coefficients (i.e., the standard deviation) is determined by the following formula:

$$\Delta b_i = \pm t \cdot \frac{S_{b_i}}{\sqrt{N}} \tag{18}$$

Here:

- t is the tabulated value of Student's criterion,
- N = 9 is the number of trials,
- t = 2.262 for P = 0.95 (i.e., a 95% confidence level).

$$\begin{aligned}
 \Delta b_0 &= 2.262 \cdot \frac{0.04368}{3} = \pm 0.0329; \\
 \Delta b_{12} &= 2.262 \cdot \frac{0.06552}{3} = \pm 0.04936; \\
 \Delta b_1 &= \Delta b_2 = 2.262 \cdot \frac{0.05349}{3} = \pm 0.0403; \\
 \Delta b_{11} &= \Delta b_{22} = 2.262 \cdot \frac{0.09266}{3} = \pm 0.0698.
 \end{aligned} \tag{19}$$

Thus, the confidence intervals for the regression coefficients are as follows:

$$\begin{aligned}
 \beta_0 &= 18,2301 \pm 0,0329 & \beta_{12} &= 0,0111 \pm 0,04936 \\
 \beta_1 &= -0,0095 \pm 0,0403 & \beta_{11} &= -0,2483 \pm 0,0698 \\
 \beta_2 &= -0,0062 \pm 0,0403 & \beta_{22} &= -0,2705 \pm 0,0698
 \end{aligned} \tag{20}$$

Taking the error into account, the significant coefficients of regression equation (3.14) give the equation the following form:

$$y = 18.2301 - 0.2483 \cdot x_1^2 - 0.2705 \cdot x_2^2. \quad (21)$$

Tables 3–4 give the values calculated from the experimental data and their mean-square deviations. Substituting the sum of the mean-square deviations from Table 4 into the formula, the adequacy (goodness-of-fit) variance for equation (3.14) is determined as follows:

$$S_{ad}^2 = \frac{\sum_{i=1}^N n \cdot (\bar{y} - \hat{y})^2}{N - (k+1)} = \frac{0.288}{8} = 0.036 \quad (22)$$

Here: N is the number of experimental series, n is the total number of trials. The adequacy of equation (3.14) is checked by means of the Fisher criterion as follows:

$$F_{calc} = \frac{S_{ad}^2}{S_{rep}^2} = \frac{0.036}{0.01717} = 2.096 \leq F_{table} = 2.16 \quad (23)$$

Table 3

Nº	Cutting height X_1 , mm	Cutting speed X_2 , mm/min	y_1	y_2	y_3	y_4	y_5	Average value, mm
1	0.8	8000	17.730	17.783	17.987	18.038	17.884	17.884
2	0.6	8000	17.876	17.773	17.979	18.030	17.722	17.876
3	0.8	7000	17.720	17.874	17.978	18.028	17.771	17.874
4	0.6	7000	17.911	17.808	18.013	18.065	17.755	17.910
5	0.6	7500	17.755	17.806	18.013	18.063	17.909	17.909
6	0.8	7500	17.726	17.880	17.983	18.034	17.777	17.880
7	0.7	7000	17.878	17.777	17.981	18.034	17.724	17.879
8	0.7	8000	17.713	17.763	17.968	18.020	17.866	17.866
9	0.7	7500	17.709	17.863	17.966	18.016	17.759	17.863

Results of the experiment to determine the dimensions of the inter-saw spacer belt of a saw-type fiber separator

Table 4

Nº	Number of trials	$\Sigma(y - \bar{y})^2$	y_i (average)	$\hat{y}_i$ (model value)	$\Delta y = y_i - \hat{y}_i$	$(\Delta y)^2$
1	5	0.01708	17.884	17.707	0.178	0.032
2	5	0.01718	17.876	17.704	0.173	0.030
3	5	0.01718	17.874	17.697	0.177	0.031
4	5	0.01723	17.910	17.738	0.172	0.030
5	5	0.01718	17.909	17.991	-0.082	0.007
6	5	0.01718	17.880	17.972	-0.092	0.008
7	5	0.01723	17.879	17.966	-0.087	0.008
8	5	0.01708	17.866	17.953	-0.087	0.008
9	5	0.01718	17.863	18.230	-0.368	0.135
Sum	45	0.155	160.94	160.96	-0.016	0.288

Results of processing the experimental data for determining the dimensions of the inter-saw spacer belt of a saw-type fiber separator

The tabulated value of the Fisher criterion, for the adequacy variance $f = (N-1) = 8$ and the reproducibility variance $f = (n-1) = 44$, is $F_{table} = 2.16$ [71]. The adequacy conditions of mathematical model (3.14) are satisfied, since $F_{calc} = 2.096 < F_{table} = 2.16$. Thus, equation (3.14) statistically describes the change in the thickness of the inter-saw spacer belt of the saw-type fiber separator obtained by laser cutting (Figs. 3–4).

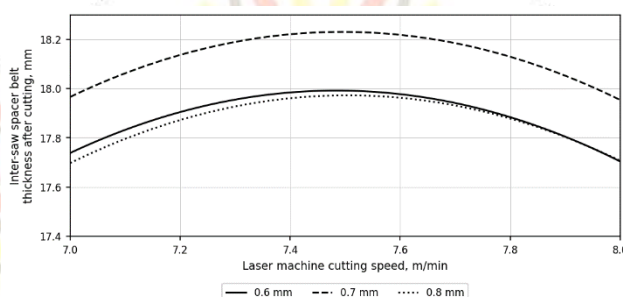


Fig. 3. Variation of the inter-saw spacer belt width as a function of cutting speed x_2 , for different values of cutting height x_1 .

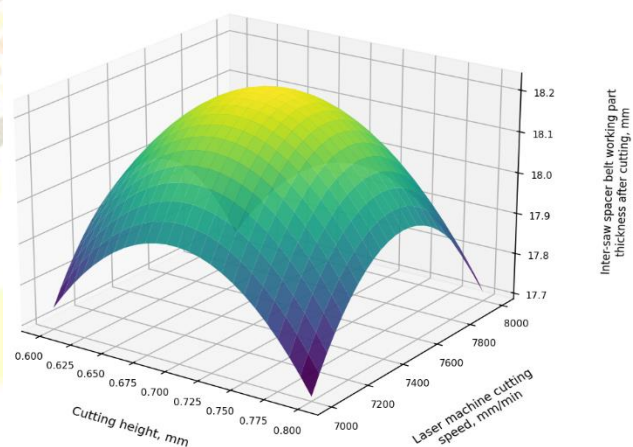


Fig. 4. Variation of the inter-saw spacer belt width as a function of cutting height x_1 and cutting speed x_2 .

On the basis of equation (3.14), a graph of the variation of the inter-saw spacer belt width as a function of cutting height x_1 was constructed for different values of cutting speed x_2 (Fig. 3). A graph of the belt width as a function of both cutting height x_1 and cutting speed x_2 was also constructed (Fig. 4).

Analysis of the graphs in Figs. 3 and 4 shows that, as the cutting speed changes from 7000 to 8000 mm/min and the cutting height changes from 0.6 to 0.8 mm, the thickness of the inter-saw spacer belt increases (from 17.697 mm to 18.23 mm). The maximum belt width of 18.23 mm was found to occur at a cutting speed of 7000 mm/min and a cutting height of 0.7 mm [8].



CONCLUSION

1. One of the methods for manufacturing the inter-saw spacer belts of a saw-type fiber separator is laser cutting technology. Analysis of this technology showed the need to study the effect of cutting height and cutting speed in the process of manufacturing the inter-saw spacer belt.

2. Taking into account the determined parameters of the cutting regime, together with the physical properties of the material and the geometric dimensions of the blank, it is possible to achieve the required accuracy when machining the parts.

3. It has been established that, in manufacturing the inter-saw spacer belt of a saw-type fiber separator by laser technology, the accuracy of producing the blank depends on the cutting height and the cutting speed. To study this process, experiments were carried out on a Bodor A3 2000W metal laser cutting machine.

4. Analysis of the graphs constructed on the basis of the regression equation shows that, as the cutting speed changes from 7000 to 8000 mm/min and the cutting height changes from 0.6 to 0.8 mm, the thickness of the inter-saw spacer belt increases (from 17.697 mm to 18.23 mm). The maximum belt width of 18.23 mm is achieved at a cutting speed of 7000 mm/min and a height of 0.7 mm.

Overall, the study confirms that mathematical planning of experiments combined with statistical analysis is an effective approach for determining rational laser cutting parameters for the manufacture of precision components of cotton-processing machinery.

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