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Predicting fabric GSM and crease recovery angle of laser engraved denim by fuzzy logic analysis

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ABSTRACT

This study intends to develop and validate a fuzzy logic based model to predict the GSM and crease recovery angle of laser engraved denim. Laser engraving is a popular method for creating a faded look in denim. Conventional fading methods have a lot of drawbacks while laser engraving is a complete solution with better productivity and less rejection rate. But the important laser parameters like Pixel Time and Dots Per Inch (DPI) influence the GSM and crease recovery angle of the treated denim. Though this relationship is nonlinear, a fuzzy logic based model has been developed to demonstrate the relationship among Pixel Time, DPI as input variables, and GSM, crease recovery angle as output variables. The developed model has been validated by trial. The Mean Relative Error was found 1.68, 2.18, and 2.25 for GSM, warp way crease recovery angle, and weft way crease recovery angle respectively. On the other hand, the coefficient of determination (R^2) was found to be 0.966, 0.952, and 0.958 for the GSM, warp way crease recovery angle, and weft way crease recovery angle respectively. The authors found that the developed model is a completely new approach to predict the GSM and crease recovery angle of the laser engraved denim and therefore can be used as a decision-making tool in the apparel designing and manufacturing which can exclude a lot of existing trial and error hassle of the process designers.

1. Introduction

Denim is a hard and sturdy fabric that has been used for a very long time as a successful fashion item [1]. Denim is very popular among people of all age groups. Traditionally denim is 3/1 warp-faced twill fabric woven with indigo

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dyed warp yarn and white weft yarn. For this color variation, one side of the fabric provides an appearance of blue while the other side looks white [1], [2]. Typically this warp dyeing is done by following a special technique called ring dyeing [3][1]. This ring dyeing helps the denim fabric to be compatible in the next dry processes. Presently different types of denim are manufactured and used [4]. Even successful approaches have been made to develop stretch denim using elastane[5]. Nowadays denim is subjected to extensive research and development [6]. Denim is normally processed before wearing as garments [7]. This processing is done by dry processes or wet washes. Fading is one of the prominent denim dry processes [2], where the colors from the face side of the fabric are removed and a worn-out appearance is created. Conventionally this process was carried out by sandblasting, hand sanding, and/ or PP application [8]. According to Sakib et al. and Sarkar et al. these processes are time-consuming, with a high rejection rate, and health hazardous for the workers involved and end customers [7], [9]. In this scenario, the laser provided the solution with very satisfactory results. Despite some limitations, lasers have shown a higher degree of accuracy and productivity. Besides, Yuan et al. describe that lasers are also used in fashion designing, fabric cutting, pleating, and even in to impart special finish to textiles [10]. Among different laser systems [11], CO_2 lasers are exclusively used for this engraving process as CO_2 lasers show good performance in case of the materials that are not a good conductor of heat and electricity [12].

Lasers are monochromatic coherent lights in low divergent beams and work by evaporating the surface on which it is focused [13]. The intensity of the evaporation normally depends on two laser parameters namely pixel time, and Dots Per Inch (DPI) of the design. Changes in these parameters affect the property of the fabric and garment on which they work.

As the laser works by evaporating the fabric surface, it affects the fabric weight (GSM). As the crease recovery angle, a property that has a close connection to the comfort, softness, and anti-wrinkle capability of fabric in a broader sense is also affected by the laser engraving. These properties have a relationship with the fabric handle and feel [14], [15] hence influences the wearers' perception about the clothing. So, designing a laser process parameter especially when these properties are required to be taken into consideration would be easy if the Crease recovery angle can be predicted effectively. Same applies to GSM as well.

Literature review exposed that, approaches have been made to determine the properties of denim fabric and garments after fading/ engraving with laser treatments [7], [9]. Most efforts have been made to determine the color properties of the laser engraved denim. In these studies, the color properties were assessed after laser fading and Kan et al. claimed that pixel time and resolution of the laser are two most prominent factors and more the laser intensity, higher the rate of color fading [16], [17]. In another study [18] the effect of technological parameters of lasers on color and structure of denim fabric has been studied and Juciene et al. concluded that the laser has a significant effect on color properties of the treated denim, mostly in the warp direction. They also found that there is a correlation between color saturation and laser intensity. Some approaches have been reported to predict the color properties of the laser faded denim by Artificial Neural Network (ANN) method. ANN is a computing method that is inspired by biological neural networks like the human brain [19]. ANN methods are being used in the field of decision making for a very long time [20]. In the field of textile engineering, the ANN model is also used [21], [22]. In a study, prediction of color properties of denim after laser treatment has been investigated by Kan et al. and the authors have reported that the ANN method can be successfully used in this field [23]. In another separate study, Kan et al. claimed that the ANN model can be used to predict the color properties of laser-treated denim with a relative error of 0-5% [24]. Similarly, another investigation [25] by Hung et al. showed that the laser parameters have an influence on the color property of treated denim and the ANN method can be used to predict that. However, the ANN method generally requires a lot of data [26], [27]. Collecting this huge amount of data is a very tough job particularly in industrial situations. That's why fuzzy-based models can be used to predict the properties of treated fabric satisfactorily with less data utilization.

Therefore, we have investigated the possibility of developing a fuzzy logic based model which can be used to predict the GSM, and warp and weft way crease recovery angle. This model is super convenient and user-friendly to predict the said properties of the laser-treated denim.

2. Methodology

A fuzzy logic based model has been developed to explain the complex relationship among the input variables namely pixel time and Dots Per Inch (DPI) and output variables GSM and crease recovery angle. To examine whether the model is capable of predicting the said properties of laser engraved denim, a trial experiment has been done in the laboratory. Finally, the data predicted by the model and actual experimental data have been analyzed to validate the credibility of the developed model.

Configuration of fuzzy logic model

The fuzzy logic system has been extensively used in different branches of researches since it was developed by Zadeh at the University of California in 1965 [28].

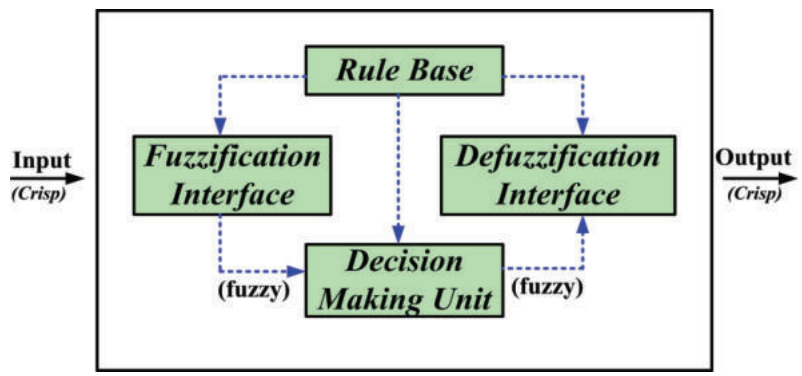

Figure 1. The basic configuration of the Fuzzy Logic System.

Figure 1 shows the four principal components of a fuzzy logic system [27], [29]–[31]. Fuzzy logic systems have four basic components. They are discussed below-

The first block of the fuzzy expert system is the fuzzification interface which is used to select the input and output variables. Membership functions have to be created for both input and output functions The numeric variables are defined in linguistic terms as low, medium, high, etc. Among different forms of membership functions, the triangle membership function is the simplest and widely used [29], [31]–[34].

Fuzzy rules are the heart of a fuzzy logic expert system [27]. These rules relate to the input and output variables and are operated by the if-then statement [30], [32], [34]. For example, for two inputs X and Y, and one output Z having linguistic variables of low and medium for X and Y respectively and medium for Z then the development of fuzzy inference rules [30], [32], [34], [35] can be presented as follows:

If X is low, and Y is medium, then Z is medium.

Mamdani and Sugeno are the two classes of fuzzy expert rule base [33], [35], [36]. Mamdani rules have been used in this particular study.

Decision making logic plays a central role in a fuzzy expert based system, as it can create human-like decision making. In this study, we have used the Mamdani max-min fuzzy inference as it assures a linear interpolation of the outputs between rules [32]. Figure 2 represents the mechanism of the fuzzy inference system in the case of two inputs and a single output.

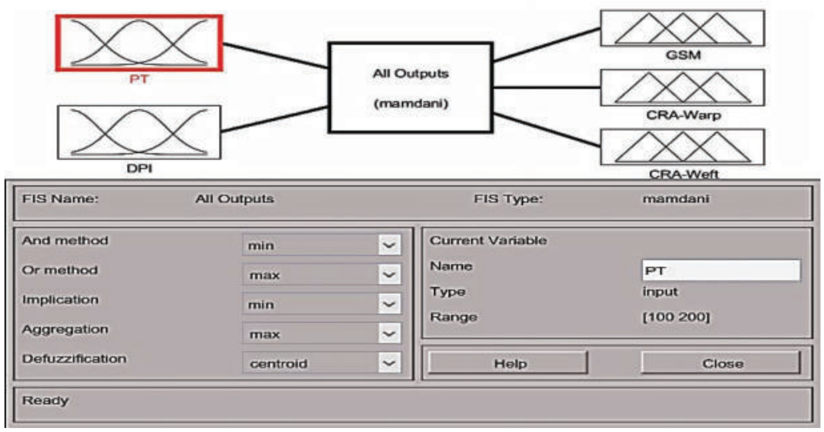

Figure 2. Fuzzy inference mechanism.

The final unit of a fuzzy expert system is the defuzzification interface [37]. The defuzzification interface converts the fuzzy output into precise crisp numeric values by combining the conclusions made by the decision making logic [35], [38]. The mostly used defuzzification method is the center of gravity (centroid) defuzzification method, as this operator assures a linear interpolation of the output between the rules [27]. The conversions of fuzzy output into a non-fuzzy crisp value Z can be expressed by using Equation I [31], [37]:

$$Z = \frac{\sum_{i=1}^{n} \mu_i * (b_i)}{\sum_{i=1}^{n} \mu_i} \quad (1)$$

where b_i is the position of the singleton and μ_i is the membership function of i rules.

Development of the Model based on Fuzzy Expert System

Two process variables namely PT (Pixel Time) and DPI (Dots Per Inch) were used as the input parameters and GSM, CRA-Warp, and CRA-weft as the output parameter for the construction of the fuzzy logic system. To develop the fuzzy model a fuzzy logic toolbox from MATLAB (Version 9.6) was used. For fuzzification, three linguistic fuzzy sets Low (L), Medium (M), and High (H) were chosen for input variables TP and DPI and they were evenly spaced and covered up the full input ranges. Five output fuzzy sets such as Low (L), Low Medium (LM), Medium (M), Medium-High (MH), and High (H), were employed for each of GSM, CRA-Warp, and CRA-Weft. Linguistic Fuzzy sets and their numeric ranges are tabulated in Table 1. After a lot of trial and error methods among the popular and mostly used parameters used in the industries, the input parameters were shortlisted. Based on the shortlist, the final set was chosen by considering which combination gives the best results by keeping the fabric in a serviceable form. the range output parameters have also been selected after applying the selected input variables in numerous combinations and considering the highest and lowest experimental values to form a range.

Table 1. Fuzzy sets and numeric values.

Parameters	Range	Linguistic fuzzy sets
PT (Pixel Time)	100-200	L, M, H
DPI (Dots Per Inch)	15-25	L, M, H
GSM	318-439	L, LM, M, MH, H
CRA-Warp	52-77	L, LM, M, MH, H
CRA-Weft	48-67	L, LM, M, MH, H

In this particular study, the triangular-shaped membership functions were used for both the input and output variables. Mamdani max-min inference mechanism and the center of gravity defuzzification method [33], [35], [36] have been applied in this research work.

Fuzzification of the used factors was performed by Equation 2, 3, 4, 5, and 6, respectively-

$$TP_{(i_1)} = \begin{cases} i_1; & 15 \leq i_1 \leq 25 \\ 0; & Otherwise \end{cases} \quad (2)$$

$$DPI_{(i_2)} = \begin{cases} i_2; & 100 \leq i_2 \leq 200 \\ 0; & Otherwise \end{cases} \quad (3)$$

$$GSM_{(o_1)} = \begin{cases} o_1; & 318 \leq o_1 \leq 439 \\ 0; & Otherwise \end{cases} \quad (4)$$

$$CRA - Warp_{(o_2)} = \begin{cases} o_2; & 52 \leq o_2 \leq 77 \\ 0; & Otherwise \end{cases} \quad (5)$$

$$CRA - Weft_{(o_3)} = \begin{cases} o_3; & 48 \leq o_3 \leq 67 \\ 0; & Otherwise \end{cases} \quad (6)$$

where, i_1 is the first input (TP) and i_2 is the second input (DPI) and $o_1, o_2, and\ o_3$ are the output (GSM, CRA-Warp, and CRA-Weft respectively) variables.

Prototype triangular-shaped fuzzy sets for the fuzzy variables namely PT, DPI, GSM, CRA-Warp, and CRA-Weft have been developed using a fuzzy toolbox from MATLAB. The membership values are presented in Figures 3 and 4. A total of nine (9) fuzzy rules have been formulated based on the opinion of industry experts of the relevant field and by following the fuzzy principles described and explained by Nakashima et al.[39], [40]. The rules are depicted in Table 2.

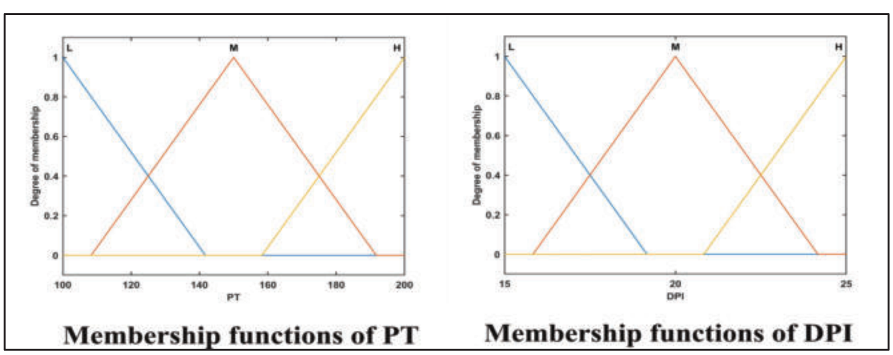

Figure 3. Membership Functions of input variables.

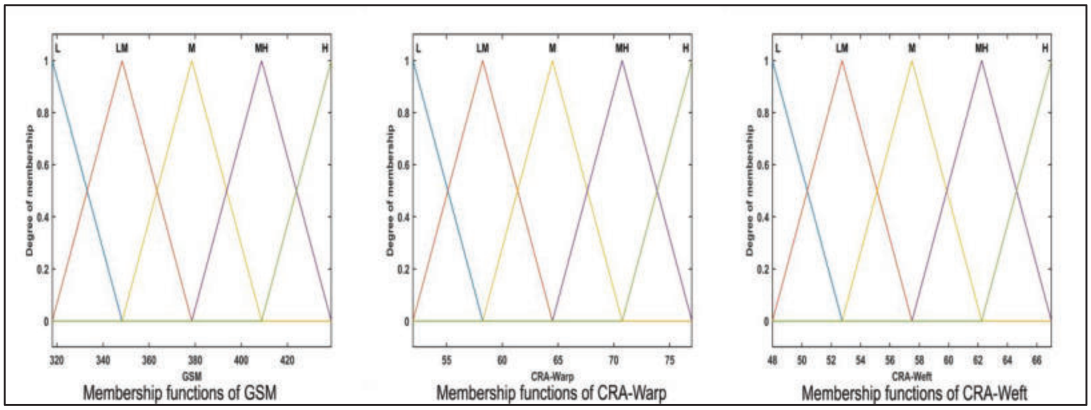

Figure 4. Membership Function of output variables.

Table 2. Fuzzy rules.

Rules	Input variables		Output variable
	PT	DPI	GSM, CRA-Warp, and CRA-Weft
Rule 1	L	L	H
Rule 2	L	M	MH
Rule 3	L	H	M
Rule 4	M	L	MH
Rule 5	M	M	M
Rule 6	M	H	LM
Rule 7	H	L	M
Rule 8	H	M	LM
Rule 9	H	H	L

Experimental procedure to validate the model

100% cotton denim fabrics were collected from the factory and leg panels were prepared. The used denim has a construction of 74 x 52/ 12 x 11, 55 inches. The GSM of the raw denim is 460 and woven in a 3/1 warp face twill arrangement. The prepared leg panels were then engraved in a CO_2 laser system (VAV Technology) according to the intended pixel time and Dots Per Inch (DPI). The design was created in the laser system with the help of photoshop software and the leg panels were placed in the work area of the laser and engraving was performed.

After engraving, the denim leg panels were normal washed following a standard recipe. The process comprised of the following steps:

Desizing

This process was carried out in material to liquor ration 1:10. The main chemical was a desizing agent (Luzyme) at a rate of 1.5 g/L. The entire desizing process was performed in a lab-scale front loading garment washing machine

(Sutlick, Singapore). The temperature was 60 °C for 20 min and the pH of the bath was maintained 7. After 10 minutes, the liquors were dropped.

Normal Wash

The panels were then washed in the same machine maintaining the same liquor ratio as desizing for 5 minutes in 30 °C using a detergent (Hostapur WCTH) at a rate of 1 g/L. After the desired time, the panels were rinsed twice in cold water.

Softening

After treating with detergent, the panels were softened with a nonionic softener (Resil) at a rate of 1.5 g/L maintaining a liquor ration 1:8. Acetic acid (35 gm.) was used in the bath to maintain pH 5.5 at room temperature for 7 minutes. The liquors were then dropped.

Hydro extracting

Hydro extracting of the washed and softened denim leg panels were performed to achieve wet pick-up of minimum 70% at 200 rpm for 3- 4 min. in a laboratory-scale hydro-extractor machine (Zanussi, Roaches International Limited, England),

Drying

The hydro extracted leg panels were then dried at 70-77 °C for 25 min. in a gas dryer (Fabcare, India).

Conditioning of the samples and experiment

The washed samples were conditioned on a flat surface for at 24 hours before testing under standard atmospheric conditions at relative humidity, RH% (65 ± 2 %) and temperature (20 ± 2 °C) [15] according to BS EN 20139 [41] and ASTM D1776 [42]. The GSM was determined according to ASTM D 3776/ D3776M-09a (2017) [43] and the warp way and weft way crease recovery angle of the prepared samples were determined according to AATCC 66-2017 [44].

The process variables for both model development and experiment are represented in Table 3.

Table 3. Range of process variables.

Process Parameters	Values		
Dots Per Inch	15	20	25
Pixel Time (μs)	100	150	200

3. Results and discussion

Fuzzy logic operation and analysis of the experimental results

Figure 5 represents the rule viewer of the fuzzy logic model. Rule viewer is the interface that displays the change in output variables as a result of changes in input variables. By this interface, the decision-makers can take the final decision to select optimum input parameters based on their requirement. In this interface, for instance, if PT is 100, and DPI is 20, then the GSM is 409, CRA-Warp (Warp way crease recovery angle) is 70.5°, and CRA-Weft (Weft way crease recovery angle) is 62.3°. Figure 6 demonstrates the surface view of the fuzzy model which explains the relationship between PT (Pixel Time) and DPI (Dots Per Inch) on the input side and GSM, CRA- Warp (Warp way crease recovery angle), and CRA-Weft (Weft way crease recovery angle) on the output side.

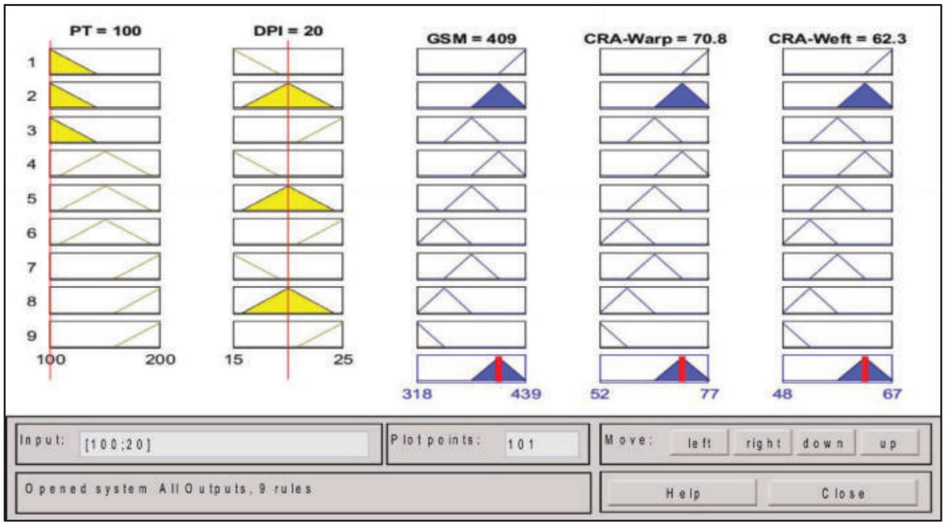

Figure 5. Rule Viewer.

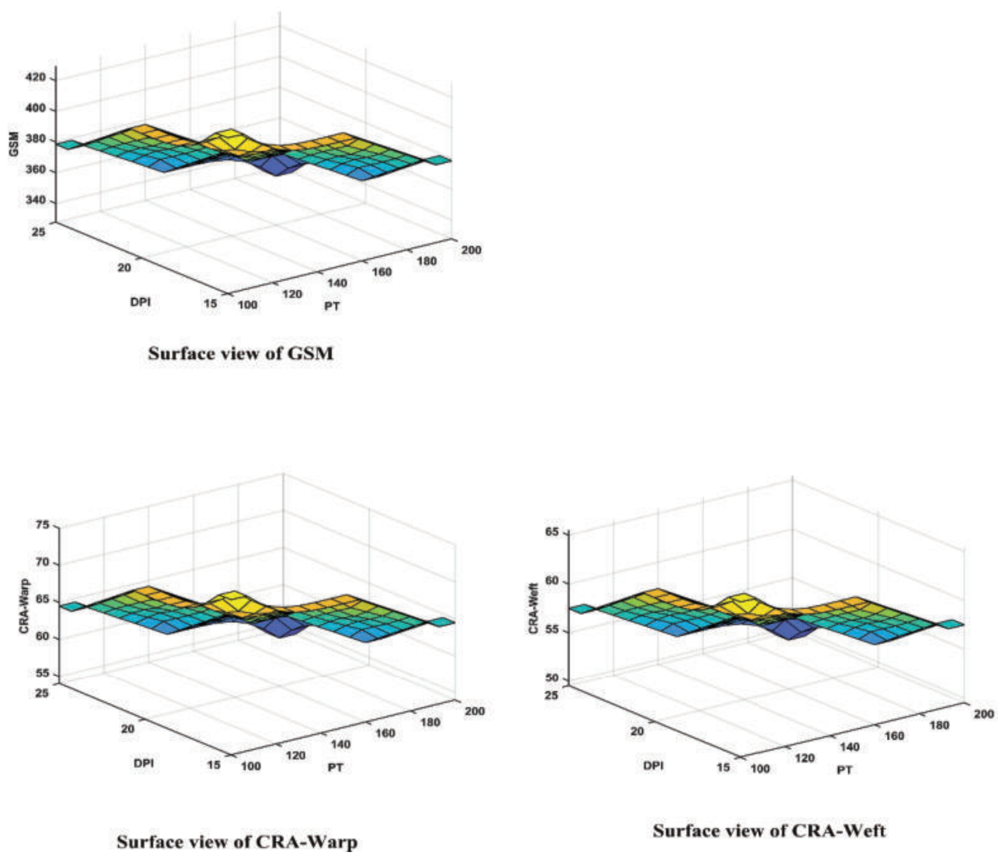

Figure 6. Surface view of the outputs.

From the study, it has been found that All the output parameters have decreased with the increment of any or both of the input parameters and vice versa. It has also been observed that the input parameters influence the output parameters significantly. As lasers work by evaporating the constituent of the fabric surface, it certainly affects the GSM and crease recovery angle (which is related to stiffness and comfort of the fabric.) of the treated fabric. As a matter of fact, choosing proper laser parameters is important for maintaining required GSM after laser treatment as well as to maintain optimum crease recovery angle. This proposed model can help in this regard to select proper pixel time and/ or DPI to get required GSM, warp way crease recovery angle, and weft way crease recovery angle and at the same time can suggest optimum input parameters to get a particular output result.

Validation of the model

The model predicted data and experimental data have been compared to validate the model. Mean absolute error (%), the correlation coefficient (R), and Co-efficient of determination (R^2) have been calculated for all of the output variables. The Co-efficient of determination (R^2) has been plotted and calculated by using SciDAVis software (Version 1.26). The total comparison of the actual and predicted results is presented in Table 4.

Table 4. Comparison of actual and predicted values of Seam Strength.

						Warp Way			Weft Way		
Sl. No.	DPI	PT	Actual GSM	The fuzzy model predicted GSM	Absolute Error (%)	Actual Crease Recovery Angle (Degree)	The fuzzy model predicted Recovery Angle (Degree)	Absolute Error (%)	Actual Crease Recovery Angle (Degree)	The fuzzy model predicted Recovery Angle (Degree)	Absolute Error (%)
1	15	100	439	429	2.33	77	75	2.67	67	65.5	2.29
2	15	150	411	409	0.49	71	70.8	0.28	64	62.3	2.73
3	15	200	385	379	1.58	66	64.5	2.33	60	57.5	4.35
4	20	100	400	409	2.2	69	70.8	2.54	62	62.3	0.48
5	20	150	375	379	1.06	65	64.5	0.78	58	57.5	0.87
6	20	200	354	348	1.72	60	58.3	2.92	54	52.7	2.47
7	25	100	372	379	1.85	62	64.5	3.88	57	57.5	0.87
8	25	150	345	348	0.86	58	58.3	0.51	51	52.7	3.13
9	25	200	318	328	3.05	52	54	3.7	48	49.5	3.03
Mean Absolute Error (%)					**1.68**			**2.18**			**2.25**
The correlation coefficient (R)					**0.983**			**0.976**			**0.979**
Co-efficient of determination (R^2)					**0.966**			**0.952**			**0.958**

Figure 7 represents the correlation between the fuzzy model predicted and the experimental/ actual values of output variables (GSM, warp way crease recovery angle, and weft way crease recovery angle) in different pixel time and DPI.

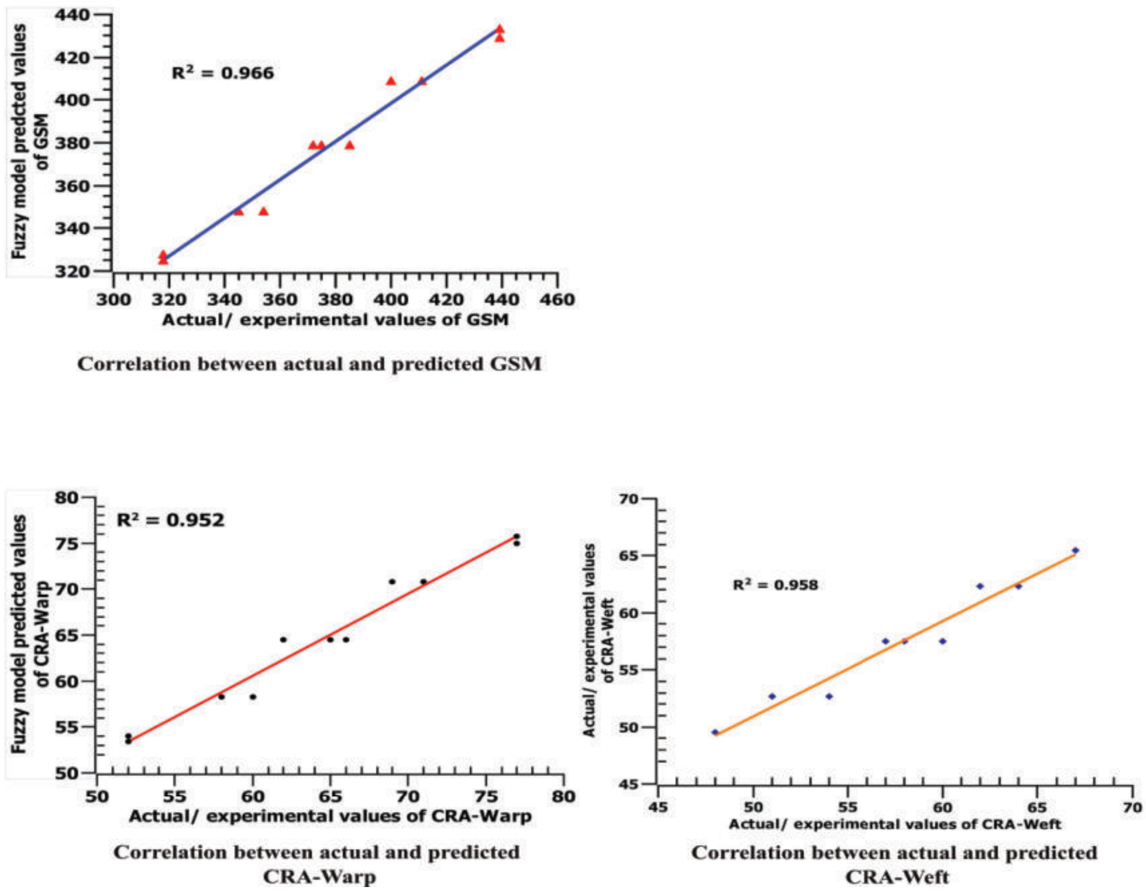

Figure 7. Linear fit of the actual and predicted data.

The Co-efficient of Determination (R^2) were found to be 0.966 (R = 0.983), 0.952 (R = 0.976), and 0.958 (R = 0.979) for GSM, warp way crease recovery angle, and weft way crease recovery angle respectively. The Mean Absolute Error between the experimental and predicted values were found to be 1.68 for GSM, 2.18 for warp way crease recovery angle (CRA-Warp), and 2.25 for weft way crease recovery angle (CRA-Weft). Therefore, it can be assumed that the predicted model can explain up to 96.6% of the total change in GSM, up to 95.2% of the total change in warp way crease recovery angle, and up to 95.8% of the total change in weft way crease recovery angle. The Mean Absolute Error was found to be 1.68, 2.18, and 2.25 which are less than 5% hence lies within the acceptable limit. The findings suggest satisfactory accuracy of the proposed model in predicting the output variables.

9. Conclusion

The proposed model is quite capable of explaining the changes in GSM, warp, and weft way crease recovery angle of laser engraved denim with response to the changes in laser pixel time and Dots Per Inch (DPI). The decision-makers in the garments sector and garments designers would be able to make decisions regarding the fine-tuning of the said parameters when required. As the model can explain the effects of laser parameters on treated fabric parameters with satisfactory accuracy, this principle can be used to predict other fabric properties. This particular investigation actually opens the door of the suitability of eliminating the trial and error method of the textile sector, which is time-consuming as well as requires a lot of loss in terms of time and material.

The conclusions may be drawn from this investigation are:

a) The Mean Absolute Error between the predicted values and experimental values of GSM, warp way crease recovery angle (CRA-Warp), and weft way crease recovery angle (CRA-Weft) were found to be 1.68, 2.18, and 2.25 respectively which is lower than the acceptable limit of 5%.
b) The correlation coefficient (R) between the predicted and experimental values of the output variables GSM, CRA-Warp, and CRA-Weft were found to be 0.983, 0.976, and 0.979 respectively.
c) The Co-efficient of determination (R^2) was found to be 0.966 for GSM, 0.952 for warp way crease recovery angle (CRA-Warp), and 0.958 for weft way crease recovery angle (CRA-Weft) which indicated a good fit of the model data with experimental data and hence suggests that the model is well compatible.

Finally, it can be concluded that the proposed model can be used in the predicting and fine-tuning of some particular parameters of laser-treated garments with response to two most important laser parameters and the principle of this model can be used for further fabric and garment properties which can save a lot of time and effort for textile professionals.

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