Optimization of Edge Banding Process Parameters Used for Particle Board and Medium Density Fiberboard

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This study determined the factors affecting peeling strength performance of edge bands, an important element of the furniture industry, and improved peeling strength performance by optimizing these factors. The independent variables were material types, amount of adhesive, feed speed, and temperature, while the dependent variable was the peeling strength. A central composite design (CCD) was used to investigate the optimal process parameters to achieve a maximum peeling strength for medium-density fiberboard (MDF) and particle board (PB). These materials were prepared using different feed speeds, temperatures, and amounts of adhesive. The CCD design based on the desirability function approach successfully achieved the optimal process parameters. An analysis of variance (ANOVA) determined the significant parameters on the peeling strength of edge banding. Maximum MDF and PB edge banding peeling strength values were calculated as 0.0706 and 0.0673 N/mm^2, respectively. In the edge banding process applied using optimum parameter levels, an increase of 8.8% and 7.17% was achieved in the peeling strength of PB and MDF samples, respectively.

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Keywords: Optimization; Edge bander; Desirability function; Wood material; Design of experiment; PVC; Peeling strength; CCD design

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INTRODUCTION

The edges of wood composite materials such as medium-density fiberboard (MDF) and particleboard (PB) need to be covered in order to improve their color, brightness, pattern, and strength properties. By covering the edges of materials such as MDF and PB with the application of edge banding, the screw and nail holding strength increases, and it prevents the edges of the wooden board from swelling due to water absorption, changing color, and mold formation.

Adhesive breakage and peeling occur frequently during use on the plastic edge banding, which is widely used in the case of panel furniture (Yuan *et al.* 2010). It has been determined that the soft peeling method is suitable for polyvinyl chloride, polypropylene, and 2-mm-thick polymethyl methacrylate edge banding. The soft peeling method can be used to reveal the effectiveness of the adhesives. For instance, peel damage has been found to occur mainly between the edge band and the hot melt adhesive (Yuan *et al.* 2011; Wen *et al.* 2012).

In the literature, there are studies on the rigidity of furniture joints made of laminated PB and MDF. In addition, the edges of the specimens were covered with 0.4-mm-thick melamine edge banding, polyvinylacetate (PVAc) (0.4, 1.0, and 2.0 mm thick), and birch veneer (0.4, 1.0 and 2.0 mm thick) (Tankut and Tankut 2010). It has been shown that the strongest joint was made of MDF with paper-based laminates that were then applied to wood-based surfaces. In compression and tensile tests, the average joint strength was approximately 17% and 18% better, respectively, compared to the second-best variant (PB and PVAc, 0.4 mm). Fathollahzadeh *et al.* (2013) subjected different types of furniture frames (made of laminated MDF and raw MDF in both edged and edgeless versions) to cyclic loading. It was determined that the strength of the edged structural elements was 1.8 times higher.

Vlaovic *et al.* (2024) reviewed the critical role of edge banding in enhancing the performance of corner joints, which are fundamental to the overall quality of panel furniture, and a targeted literature research was conducted across key databases. It was shown that edge bandings have an important role for reinforcing corner joint strength, as different materials exhibit varying degrees of resistance to impact, scratches, and abrasion and safeguarding furniture surfaces.

Lyu *et al.* (2017) determined peeling strength of polyvinyl chloride (PVC) edge band on the curved edge part using experimental method. They defined the influence of factors (temperature of applied adhesive, adhesive dosage, and feed rate) on peeling strength of edge band from the curved edge part. The result showed that temperature of applied adhesive, adhesive dosage and feed rate affected the peeling strength of PVC edge band.

In another study, various gauges were created for different edging strips made of beech wood, melamine, and PVC. Using the generated computer program allowed for the estimation of the adhesion strength and visual quality of the edged furniture components before their actual production. Input parameters were the type of edge banding material, power save mode, and perfect appearance (appearance), while the output variable was adhesion strength (Merdzhanov 2018).

Chen *et al.* (2022) developed a method for detecting edge band defects that occur in the furniture industry. It is an engineered system for defect detection of edge-glued wood panels that receives defect entry images from a camera as raw image and laser aligned image.

In other related work, the surface preparation was found to play a critical role in optimal glue performance (Triboulot *et al.* 1995). Other topics of importance include maintaining minimal angular deviation, so as to improve bonding strength (Džincic and Palija 2023) with particleboard material type. Guidelines for improving edge band durability and adhesion in furniture were established (Lyu *et al.* 2017). It was found that thicker edge bands, such as 2 mm PVC, enhance bending and tensile strength (Sacli 2015). With PVC edge bands material type, it was found that rounded edge modifications improve joint durability and lifetime (Kubit *et al*. 2023) with particleboard, and a glued joint material type was studied.

In the furniture industry, there are three main types of edge bands: melamine based, polyvinyl chloride (PVC) based, and Acrylonitrile Butadiene Styrene (ABS) based. The PVC and melamine-based edge bands are the most preferred in furniture production. Edge bands are offered to furniture manufacturers with 0.40 mm, 0.80 mm, 1 mm, and 2 mm thickness options. Because furniture manufacturers work in a competitive environment, 0.80 mm edge bands are more economical.

Recently, machine learning algorithms, such as support vector machine (SVM), artificial neural network (ANN), naive Bayesian (NB), decision tree (DT), and experimental design methods (FCD), such as central composite design (CCD), face center design, *etc.*, and Taguchi and Box-Bohen design (BBD), are widely used in solving various engineering problems. The integration of experimental design with machine learning algorithms to predict quality attributes has become popular (Lauro *et al.* 2015; Laha *et al.* 2015; Alipanahpour *et al.* 2016; Sarikaya and Gullu 2016; Panigrahi and Behera 2020).

However, accurate experimental data forms the basis of all modeling work for development, validation testing, or parameterization. Statistical Experiment Design (DoE) is a valuable tool to obtain the maximum amount of relevant data with minimal economic cost and time, to reduce the time and effort associated with the experiment. The DoE has successfully been used in different industries and areas, such as, agricultural, energy and bioenergy, pharmaceutical, fuel cells, analytical chemistry, microencapsulation, and chemical and biochemical processes (Bas and Boyacı 2007; Davim *et al.* 2008; Gaitonde *et al.* 2008; Wahdame *et al* 2009; Callao 2014; Weissman 2015; Makela 2017; Paulo and Santos 2017; Politis *et al.* 2017; Montgomery 2017).

For this reason, it was decided to systematically investigate the changes caused by the edge band application parameters on the material. The experimental design method has been used to investigate and optimize the effects of many independent changes. In particular, factorial designs are widely used both to investigate the interactions of independent variables with each other and to reduce the experimental cost (Adiguzel *et al.* 2019; Hazir and Ozan 2019; Hazir *et al.* 2020). The 2^k design was used to estimate the expected performance and deviation index. This method was shown to produce reasonable estimates with fewer samples especially for systems with significant interaction effects and nonlinear behavior (Yu and Ishii 1998). In the present study, experimental design methodology was used to reduce experimental costs and systematically determine process parameters. Analysis of variance was used to determine significant parameters. The desirability function was used to find the optimum levels of the identified variables. The results obtained using the process parameter levels recommended by the manufacturer were compared with the peeling strength obtained using the optimum process parameter levels.

EXPERIMENTAL

Specimen Selection and Preparation

In this study, MDF and PB are selected as workpiece materials, as these are widely used in the furniture industry. They were supplied by a MDF and PB manufacturer (Kastamonu Entegre Company), and the samples were cut with a size of 400 mm × 50 mm × 18 mm. Each specimen was weighed, and dimensions were calculated at an accuracy level of 0.1 g and 0.01 mm, respectively. Properties of MDF and PB are given in Table 1.

Table 1. Properties of MDF and PB

Material Type	Tensile Strength (N/mm^2)	Bending Strength (N/mm^2)	Modulus of Elasticity (N/mm^2)	Density (kg/m^3)
MDF	0.50	18	2100	701
PB	0.35	10.5	1500	645

The edge banding machine enables the edges of wood-based materials to be bonded with different edge bands. The technical specifications of the machine used in the study are given in Table 2. The PVC is a thermoplastic material used in the production of edge bands in the furniture industry. With its flexible structure, it is suitable for machining. It provides ideal use for straight and curved edge banding. Bands (0.8 mm PVC samples) were selected for the evaluation of the edge band performance test.

Table 2. Technical Specifications of the Edge Bander Machine

Band Thickness	Wood Material Thickness	Wood Material Width	Processing Speed	Processing Height
0.4 to 3.0 mm	8 to 60 mm	40 to 100 mm	10 to 25 m/min	950 mm

Edge Banding Performance Test

Edge banding performance was determined with TS EN 1464 (2010). Test pieces were prepared by gluing a 400 mm x 50 mm piece to the long sides as described and recommended by the side band manufacturer. It was passed between the two rollers at the bottom of the apparatus and attached to the holding jaws at the bottom. Then, the experiment was started by adjusting the test speed to 20 mm/min. The lowest and highest peeling force was determined, excluding the first 25 mm and the last 25 mm. Edge banding performance test for MDF and PB is shown in Fig. 1.

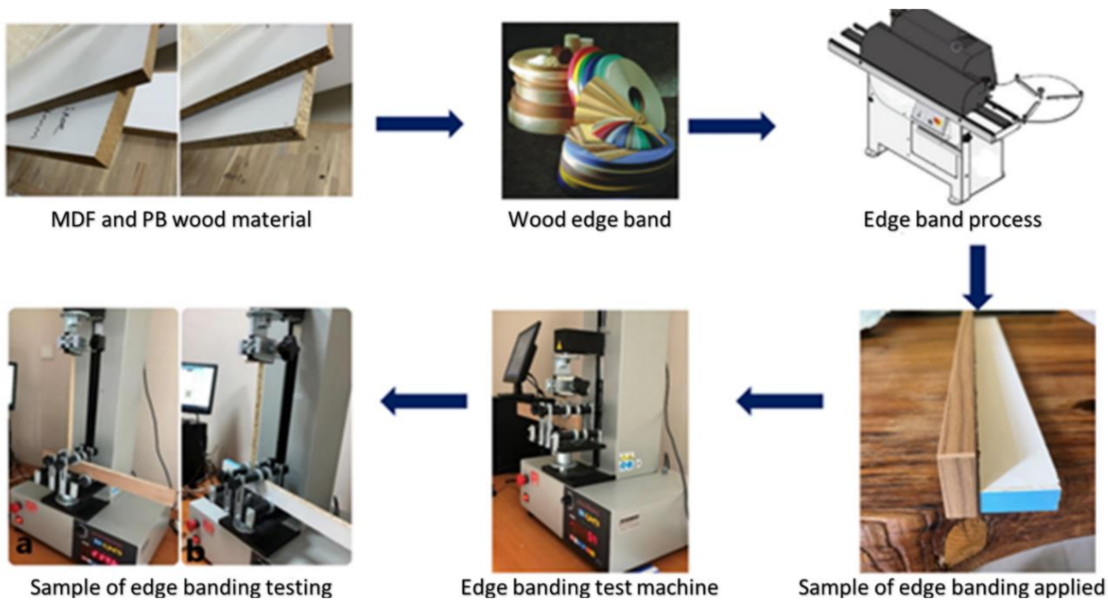

Fig. 1. Banding performance test for MDF and PB

Experimental Procedure

Investigation of the variables affecting the performance of the edge banding and optimization of these variables was carried out in 8 stages. The experimental design and methods used in the study are shown schematically in Fig. 2.

The phases were as follows:

1. Peeling strength was determined for both MDF and PB by conducting experiments using the process parameters and levels recommended by the edge banding manufacturer and edge banding supplier.

2. The process variables were selected as feed rate, temperature, material type, and amount of adhesive.

3. The experimental design used for conducting the experiment consisted of three levels, four factors, and one replicate.

4. An ANOVA (Minitab 2021, State College, PA, USA) was used to determine the interactive and effective factors for edge banding process. Plots of interactive and main were employed to investigate the relationship between the input and output parameters.

5. These data were used to construct and evaluate the regression model. A multiple regression model was used to evaluate the factors.

6. Different mathematical models were developed for both MDF and PB. Normal probability plot (NPP), R-square(R2), Adjust-R-square (Adj- R2), and F test were used to determine the performance of the models.

7. Desirability function was applied for maximizing the peeling strength.

8. The results obtained using the process parameters and levels suggested by the edge banding machine manufacturer and edge banding suppliers were compared with the results obtained as a result of optimization of the process parameters using the desirability function.

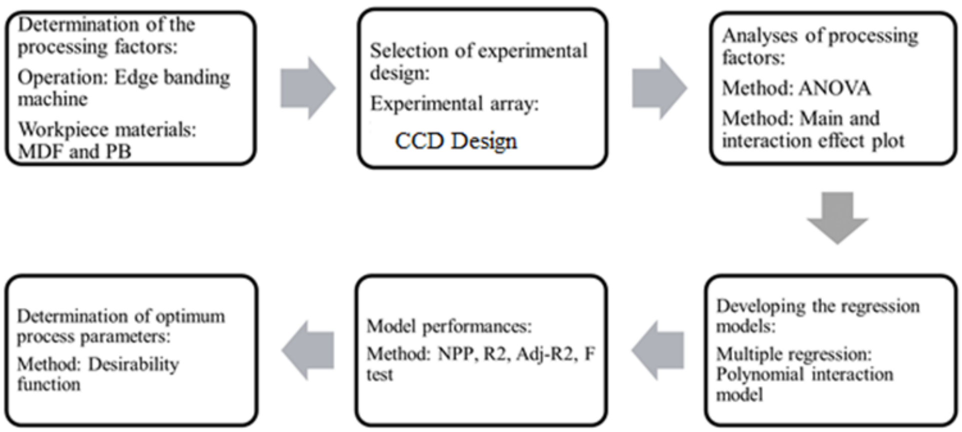

Fig. 2. Schematic diagram for the experimental design used in the present study

Experimental design

Central Composite Design (CCD) is an efficient and ideal method for investigating important parameters of a response (Montgomery 2017) and for determining effective parameters. Because it is a statistical-based method, it is not possible to evaluate it with the classical experimental design, and it also evaluates the interactions between influential variables (Antony 2014). In addition, this design has many advantages such as fewer experimental runs and data analysis with graphical methods. The mathematical model is another advantage of this design.

Suitable for inferring quadratic polynomial equations, CCD is discussed for use to optimize various research problems. A CCD has three sets of design points:

(1) Two-level factorial and fractional factorial design points ($2k$), is made up possible combinations of $+1$ and -1 levels of factor;

(2) Suppose a distance α from the center to form the quadratic organization, $2k$ axis points fixed axially (known as star points);

In CCD, it is important to examine the alpha (α) control, as it will be based on the center of the axial points in the test area. Depending on alpha spending, the design is spherical, orthogonal, rotatable, or face centered. In practice, between face-centered and sphere, and its implementation is as follows in Eq. 1,

$$\alpha = (2^k)^{0.25} \quad (1)$$

The alpha value is equal to 1 because it provides the position of the axial point within the factorial part region. It is known as face-centered design and provides three levels for parameters to be put into the design of experimental matrix. The experimental results obtained were analyzed using the response surface regression procedure of the statistical analysis approach. The relationship between responses and independent parameters is obtained using the quadratic polynomial equation Eq. 2,

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_{ii}^2 + \sum_{i=1}^{k} \sum_{j=1}^{k} \beta_{ij} x_i x_j + e \quad (2)$$

where Y shows the responses, k is the number independent variables, β_0 is an intercept, i, ii, and ij with β represent the coefficient values for linear, quadratic, and interaction effects, respectively, and xi and xj represents the coded levels for independent factors.

In this study, feed rate, temperature, material type, and amount of adhesive were used as the independent variables. Process parameters were obtained by applying face centered design. Variables coded as (- 1), (0), and (+1) are shown in Table 3.

Table 3. Process Parameters and Levels

Symbol	Parameters	Unit	Level (-1)	Level (0)	Level (+1)
A	Feed speed	m/min	10	12.5	15
B	Amount of adhesive	g/m^2	350	365	380
C	Temperature	C	150	165	180
D	Material type	-	MDF	-	PB

RESULTS AND DISCUSSION

Results of the Parameters and Levels Recommended by the Manufacturers

The process parameters and levels recommended by the edge banding machine manufacturer and edge banding suppliers were a temperature of 180 °C, feed speed of 14 m/min, and adhesive amount of 380 g/m^2. The peel strength results obtained using these parameters and their levels are given in Table 4.

Table 4. Process Parameters and Levels

Experimental Order	Peeling Strength of PB (N/mm^2)	Peeling Strength of MDF (N/mm^2)
1	0.062	0.066
2	0.064	0.068
3	0.059	0.065
4	0.063	0.066
5	0.066	0.064
6	0.060	0.067
7	0.057	0.062
8	0.059	0.064
9	0.061	0.065
10	0.062	0.068

The results obtained using the probability plot are given in Fig. 3. According to the results, the mean peeling strength and standard deviation for PB were found to be 0.0613 N/mm² and 0.0026, respectively. These results were found to be 0.0655 N/mm² and 0.0019 for MDF, respectively. When Anderson darling (AD) and P value (P) results were evaluated, it can be seen that the results were consistent.

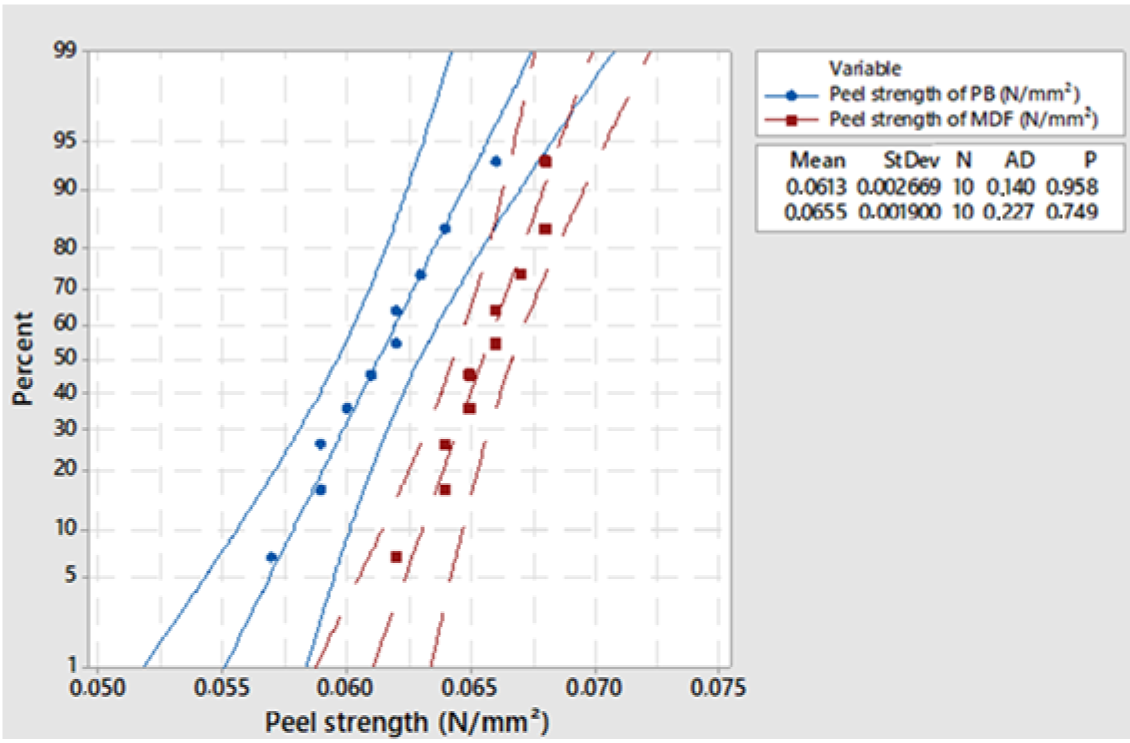

Fig. 3. Probability plot result for MDF and PB

Experimental Design and ANOVA Results Obtained Using CCD Design

Four factors at three level CCD designs, applying a total of 40 test runs (20 test for MDF, 20 test for PB), were found as a result of evaluating the peeling strength. Process parameters and levels are given in Table 5. The results obtained using these values are given in Table 6.

In this study, ANOVA was used to investigate the factors affecting the peeling strength performance of the edge band. The ANOVA result is given in Table 6. According to the results, A and D were found to be important. At the same time, when the interactions between the factors were examined, AB, AD, and BD were found to be significant. The adequacy of the ANOVA was determined using R-square and Adj-R-square values. These values were found as 79.93% and 69.89%, respectively.

Main Effect Results

The main effects plot was used to determine the effective factors (Fig.4). This plot is the graph of the mean response result of the variables of a process and the levels of their variables. According to the results, peeling strength reached maximum levels between 10 m/min and 13 m/min for feed speed. Maximum peeling strength was achieved between 360 and 373 g/m^2 of applied adhesive amount. Maximum peeling strength was found at application temperatures between 160 and 180 °C. The peeling strength of MDF was found to be higher than that of PB.

Table 5. Result of Experimental Design

Feed Speed (m/min)	Amount of Adhesive (g/m^2)	Temperature (°C)	Peeling Strength of MDF (N/mm²)	Peeling Strength of PB (N/mm²)
12.5	365	165	0.0576	0.0544
10.0	365	165	0.0649	0.0610
12.5	380	165	0.0449	0.0562
15	380	180	0.0563	0.0427
12.5	365	180	0.0641	0.0410
15	350	180	0.0594	0.0585
12.5	365	165	0.0527	0.0494
12.5	365	165	0.0550	0.0405
15	350	150	0.0571	0.0638
12.5	365	150	0.0597	0.0505
10	380	150	0.0493	0.0571
12.5	365	165	0.0623	0.0486
15	365	165	0.0653	0.0525
10	350	150	0.0571	0.0491
12.5	365	165	0.0557	0.0471
12.5	350	165	0.0481	0.0525
10	350	180	0.0556	0.0555
10	380	180	0.0541	0.0532
12.5	365	165	0.0632	0.0532
15	380	150	0.0482	0.0633

Table 6. Result of ANOVA

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	13	0.001326	0.000102	7.96	0.000
Linear	4	0.000263	0.000066	5.14	0.003
A	1	0.000085	0.000085	6.66	0.016
B	1	0.000007	0.000007	0.51	0.480
C	1	0.000009	0.000009	0.71	0.409
D	1	0.000163	0.000163	12.69	0.001
Square	3	0.000676	0.000225	17.59	0.000
A*A	1	0.000192	0,000192	14.95	0.001
B*B	1	0.000652	0.000652	50.95	0.000
C*C	1	0.000035	0.000035	2.74	0.110
2-Way	6	0.000386	0.000064	5.03	0.002
Interaction					
A*B	1	0.000144	0.000144	11.23	0.002
A*D	1	0.000135	0.000135	10.52	0.003
B*C	1	0.000012	0.000012	0.96	0.337
B*D	1	0.000070	0.000070	5.50	0.027
C*D	1	0.000025	0.000025	1.97	0.173
Error	26	0.000333	0.000013		
Lack-of-Fit	16	0.000208	0.000013	1.04	0.492
Pure Error	10	0.000125	0.000013		
Total	39	0.001659			

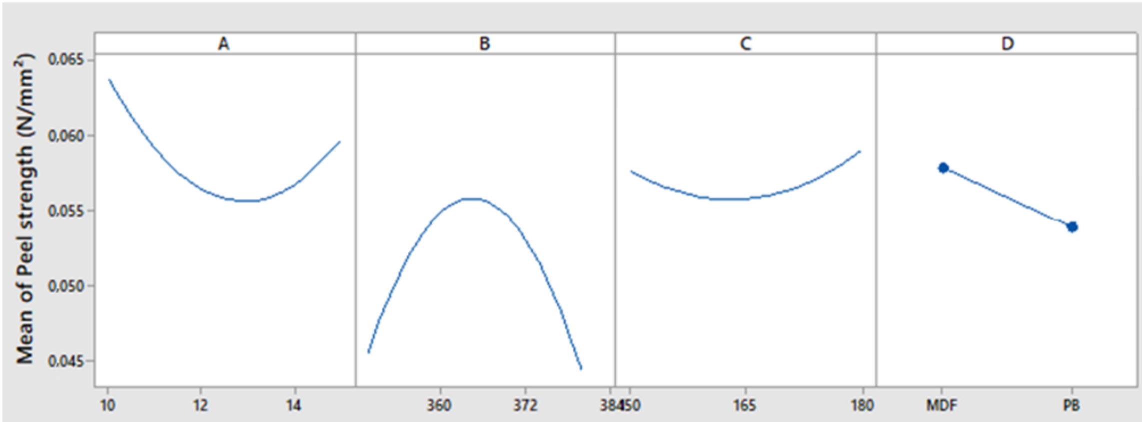

Fig. 4. Main effect plot for peeling strength; A: feed speed (m/min), B: amount of adhesive (g/m^2), C: Temperature (°C), D: Material type

Interaction Plot Result

In the study, the factors affecting the peeling strength of the edge band, as well as the interaction effects, were evaluated using interaction plot, and results are shown in Fig. 5. It can be seen that the interaction between feed rate and material type was significant. Maximum peeling strength was obtained in MDF samples and at high feed speed. When the interaction between the feed speed and the amount of adhesive is examined, it can be seen that the peeling strength was maximum in 365 g/m^2 applications. When the interaction between the amount of adhesive and the material type was calculated, it is apparent that the maximum peeling strength was in MDF and 350 g/m^2 applications. This result was also supported by variance analysis.

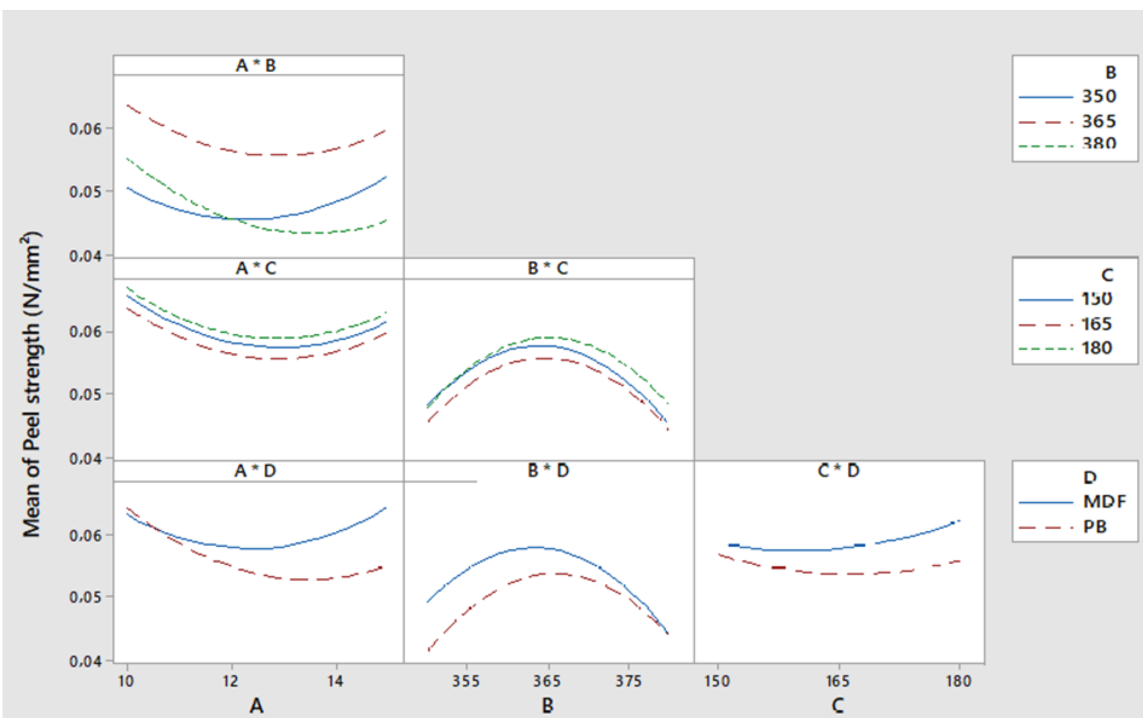

Fig. 5. Interaction plot for peeling strength; (A: feed speed (m/min), B: amount of adhesive (g/m^2), C: Temperature (°C), D: Material type)

Model Adequacy

To evaluate the accuracy of the model used in the study, the results of R-square, adjusted-R square, and lack of fit were evaluated in the first stage. According to the results obtained, R-square and adjusted R-square scores were found to be close to 1. Because the Lack of fit value was $P < 0.05$, the model was found to be significant. In the second step of the accuracy assessment, normal probability plot and histogram diagrams of residuals were used. As the results were evaluated together, there was no evidence to reject the established model. Result of residuals plot is shown in Fig. 6.

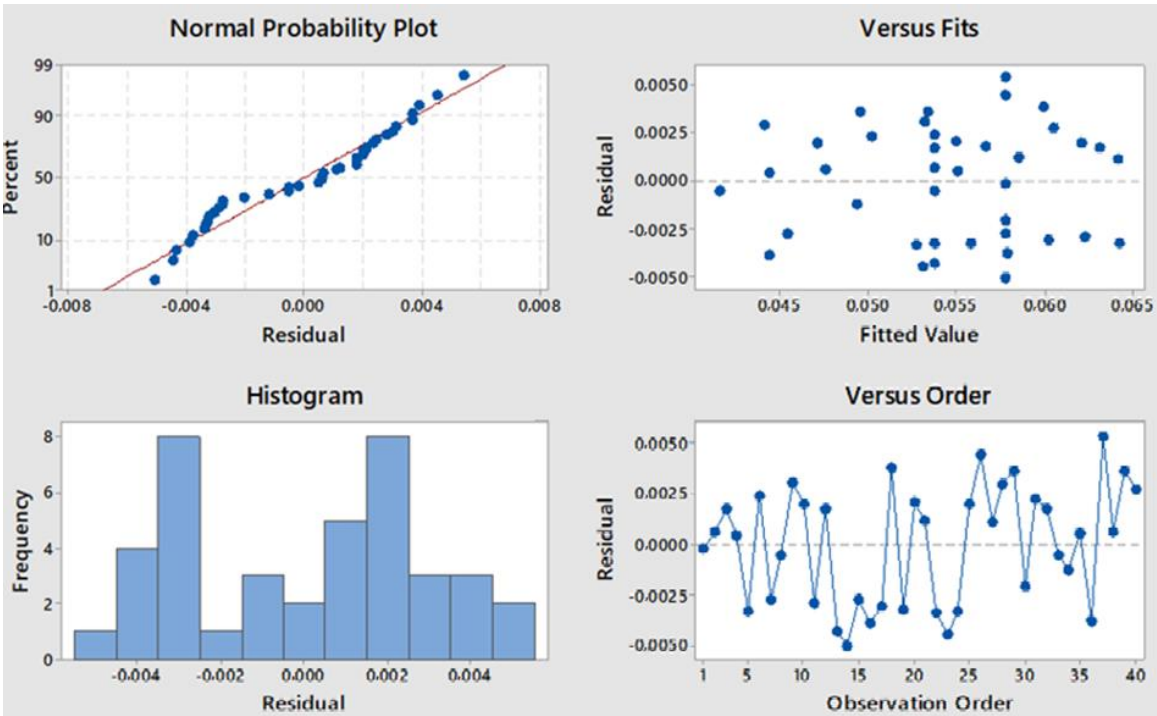

Fig. 6. Residuals plot for peeling strength

Optimization of Process Parameters

Desirability function is widely applied to optimize process variables of various engineering problems. It values between 0 and 1. If d increases, the desirability value of the corresponding response also increases. In the present study, quality characteristic was determined as the transformation of peeling strength. This value is calculated by using Eq. 3: T indicates the target value of the ith output, y_i, L is the acceptable lower limit value, and W is the weight.

$$d_i = \begin{cases} 0 \; y_i < L \\ \left(\frac{y_i}{T-L}\right)^{w} \quad L \leq y_i \leq T \\ (1) \; y_i > T \end{cases} \tag{3}$$

In Fig. 7, the resulted peeling strength of MDF was 0.0706 N/mm^2. Additionally, the value of desirability (d) was calculated as 1. This result means that the factor levels provided the global optimum solution. According to these results, the maximum peeling strength for MDF was achieved with a feed speed of 15 m/min, adhesive amount of 364.24 g/m^2, and temperature of 180 °C.

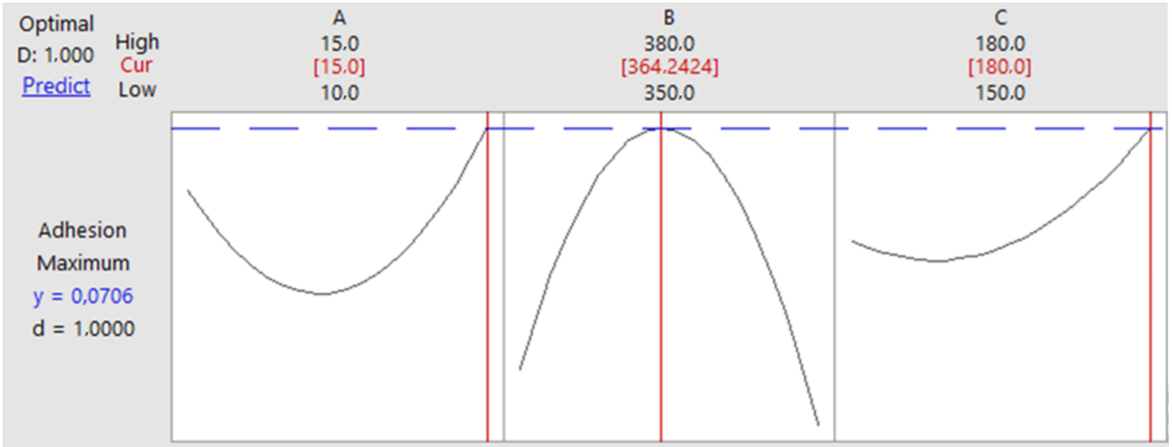

Fig. 7. Optimum process conditions for MDF; A: feed speed, B: amount of adhesive, C: temperature

In Fig. 8, the peeling strength of PB was found to be 0.0673 N/mm^2. Additionally, the value of desirability (*d*) was calculated as 1. This result means that the factor levels provided the global optimum solution. According to these results, the maximum peeling strength for PB was achieved with a feed speed of 10 m/min, adhesive amount of 370.90 g/m^2, and temperature of 180 °C. When the results of both solutions are evaluated together, it is apparent that they were compatible with the results of the main and interaction plot.

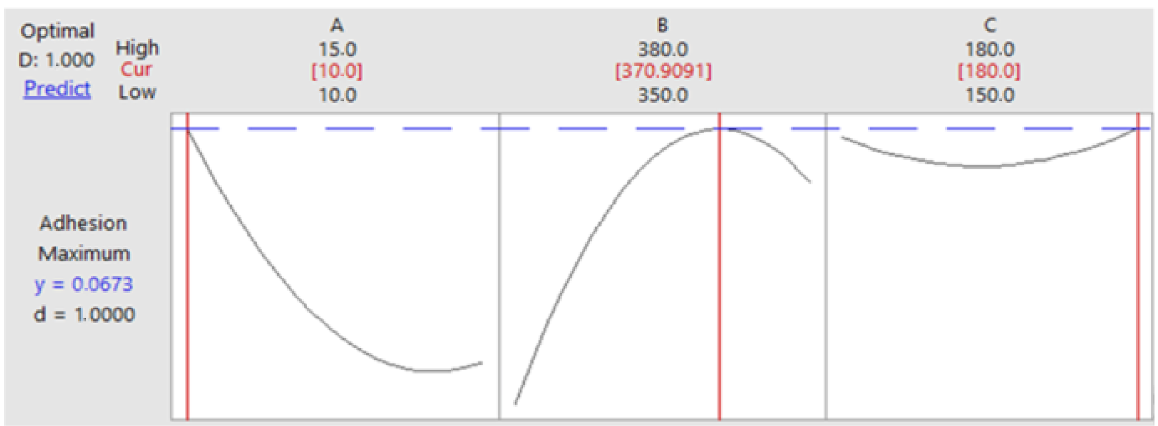

Fig. 8. Optimum process conditions for PB; A: feed speed, B: amount of adhesive, C: temperature

Comparison of Results

In this study, the peeling strength results obtained using the process parameters and levels recommended by edge banding suppliers and machine manufacturers (P1-PB and P1-MDF) are compared with the results obtained using the optimum parameter levels (P2-PB and P2-MDF) obtained by using the CCD design and desirability function together and are given in Tables 7 and 8. Comparison of process parameters and levels are given in Table 7.

Table 7. Comparison of Process Parameter Levels

Process Type	Material Type	Edge Banding Machine Parameters		
		Temperature (°C)	Feed Speed (m/min)	Amount of Adhesive (g/m^2)
(P1-PB)	PB	180	14	380
(P1-MDF)	MDF	180	14	380
(P2-PB)	PB	180	10	370
(P2-MDF)	MDF	180	15	364

Peeling strength results obtained using the process parameters and levels recommended by edge banding suppliers and machine manufacturers (10 experiments for P1-PB and 10 experiments for P1-MDF), and peeling strength results obtained using the optimum parameter levels (10 experiments for P2-PB and 10 experiments for P2-MDF) are given in Table 8.

Table 8. Comparison of Peeling Strength Results

Process	Process Parameters and Levels P1		Process Parameters and Levels P2	
Experimental Order	Peeling strength of PB (N/mm²) (P1-PB)	Peeling strength of MDF (N/mm²) (P1-MDF)	Peeling strength of PB (N/mm²) (P2-PB)	Peeling strength of MDF (N/mm²) (P2-MDF)
1	0.062	0.066	0.068	0.072
2	0.064	0.068	0.066	0.068
3	0.059	0.065	0.070	0.070
4	0.063	0.066	0.067	0.069
5	0.066	0.064	0.069	0.072
6	0.060	0.067	0.068	0.071
7	0.057	0.062	0.067	0.070
8	0.059	0.064	0.064	0.074
9	0.061	0.065	0.065	0.071
10	0.062	0.068	0.063	0.065

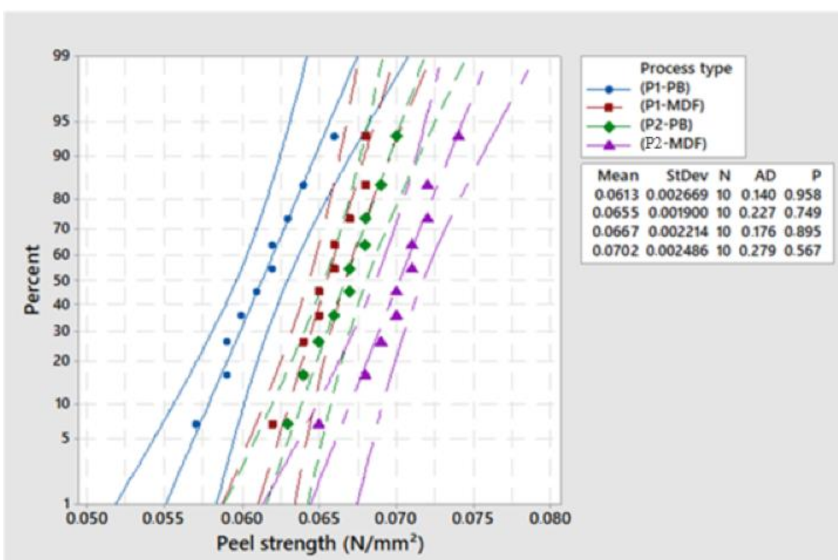

Fig. 9. Probability plot results of peeling strength for process type

The results obtained using the probability plot are given in Fig. 9. According to the results, the mean peeling strength and standard deviation (StDev) for (P1-PB) were found to be 0.0613 N/mm² and 0.0026, respectively. These results were found to be 0.0655 N/mm² and 0.0019 for (P1-MDF), respectively. Corresponding results for (P2-PB) and (P2-MDF) were 0.066 N/mm² and 0.070 N/mm²; and 0.0022 and 0.0024, respectively. When Anderson darling (AD) and P value (P) results were evaluated, it can be seen that these results were consistent. The number of samples (N) applied for each process is 40 (10 x 4).

CONCLUSIONS

The central composite design (CCD) and desirability function approach were applied to determine the effective factors and factor levels for maximizing the peeling strength. Amount of adhesive, feed speed, and temperature were used as continuous variables while material types, such as medium-density fiberboard (MDF) and particleboard (PB), were selected as discrete variables. Main and interaction plots were applied to determine the effective factor and the interaction between the factors.

1. The peeling strength of the edge banding was found to be highly affected by the feed speed and the material type. Further, the interaction between the feed speed and the amount of adhesive affects the peeling strength as well as the interaction between feed speed and material type. A similar result was found between the type of material and the amount of adhesive.
2. Because the MDF and PB have some different properties, two different optimization models were developed for MDF and PB.
3. The R^2 and R^2-adjusted results indicate that the results were statistically consistent, as they were close to 1, and the residuals did not form a pattern in tests of normal distribution.
4. The maximum peeling strength of MDF and PB values were calculated as 0.0706 and 0.0673 N/mm^2, respectively.
5. Results of feed speed, amount of adhesive, and temperature of 15 m/min, 364.24 g/m^2, and 180 °C were considered as optimum processing conditions, respectively, for MDF. Corresponding values for the PB were 10 m/min, 370.90 g/m^2, and 180 °C.
6. When (P1-PB) and (P2-PB) results were compared, the peeling strength result obtained using (P2-PB) process levels was found to be 8.8% higher than (P1-PB), while there was a 2.7% decrease in the amount of adhesive used.
7. When (P1-MDF) and (P2-MDF) results were compared, the peeling strength result obtained using (P2-MDF) process levels was found to be 7.17% higher than (P1-MDF), while there was a 4.39% decrease in the amount of adhesive used.

In this study, the most suitable processing conditions for both MDF and PB were determined by determining the factors affecting the peeling strength of the edge band for different processing conditions and for different materials. It was found that when optimum process parameter levels were used, peeling strength values increased despite the decrease in the amount of adhesive used.

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