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Research Article

Providing Regression Models for Predicting the Springback of Al1050 Reinforced with Carbon, Kevlar and Glass Woven Fiber

S. Moradi, B. Ranjbar, V. Moradi and A. Adelkhani*

Department of Mechanical Engineering, Kermanshah Branch, Islamic Azad University, Kermanshah, Iran

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ABSTRACT

Fiber metal layered composites (FMLCs) are widely used in industries such as aerospace due to their superior mechanical properties and lightweight nature. Compared to aluminum alloys and composite materials, FMLCs offer better properties. In this study, three-layer samples were made with Al1050 on the outer layers and Kevlar, carbon, and glass fibers as the core. The bending properties of these FMLCs were analyzed both numerically and experimentally. The experimental samples were made using different fibers with two angles of 0°- 90° and $\pm45^\circ$. Springback was investigated using a U-shaped bending die. The effects of punch speed (V), fibers angle (Θ), and punch radius (R_P) on the springback (S_b) of the samples were evaluated. The experimental and simulation results indicate that reducing punch radius and speed leads to a decrease in springback. Furthermore, springback was lower in 0°- 90° samples compared to the $\pm45^\circ$ ones. Based on the findings, three regression models were developed for springback prediction and the models demonstrated acceptable accuracy.

1. Introduction

Experts have increasingly focused on the use of composites over recent decades. The growing demand in the airplane industry to make light and high-function structures has led to a significant increase in composite material utilization. Fiber-metal alloys have numerous advantages in comparison with metal alloys, especially when considering their high strength-to-weight ratio [1].

Some characteristics of metals, such as fatigue, corrosion, and low strength against impact, can be compensated through the utilization of composite materials [2, 3]. Fiber metal layered composites (FMLCs) have the advantages of both metals and composite materials, making them highly promising

* Corresponding author
E-mail address: ali.adelkhani@iau.ac.ir (A. Adelkhani)
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candidates for applications in the aviation industry [4]. Consequently, selecting the optimal FMLC for a specific aircraft component is of paramount importance [5, 6].

A critical objective of the bending process is achieving the precise dimension and the desired final shape of the specimen. Springback, which occurs after unloading, reduces the accuracy of the final samples. Naik et al. (2023) [7] analyzed a sandwich panel using finite element methods in a V-shaped die during the bending process. Huang (1995) [8] conducted research on simulating finite elements of the bending process in multilayer sheets of steel-polymer-steel. Yuen et al. (1996) [9] presented a general solution for predicting springback in multilayer sheets. In another study, Takiguchi and Fusahito (2003) [10] investigated the deformation and strength characteristics of adhesive-laminated alloy sheets under plastic bending. Hino et al. (2003) [11] investigated the springback phenomenon in double-layered sheet metal consisting of a layer of pure aluminum and a layer of stainless steel. Comptston (2004) [12] compared surface strain in stamp-formed aluminum and aluminum polypropylene laminate, using 5052 aluminums and enforced propylene. Young et al. (2006) [13] studied the springback characteristics of FMLs in the brake forming process. Frostig (2009) [14] presented research on sandwich panels with a transversely flexible core using a high order theoretical approach. Parsa et al. (2009) [15] conducted an experimental and finite element study on the springback of double-curved aluminum/polypropylene/aluminum sandwich panels. Sokolova et al. (2011) [16] investigated metal-polymer-metal sandwiches with localized metal reinforcements.

Liu et al. (2012) [17] studied the effect of adhesion strength between surfaces on the ductility of aluminum 5052/polyethylene/aluminum 5052. Cheraghi et al. (2021) [18] examined the effects of holding force, die radius, pin radius, and pin distance on springback during a stretch bending test on st12 steel. Keipour et al. [19] researched the shaped draw bending process of FMLs, evaluating the effect of layering, channel depth, and core thickness on the springback angle through both experimental and numerical methods. Additionally, the bending and springback behaviors of aluminum-polymer sheets were assessed by analyzing pressure distribution and main material tension. An analytical model was extracted to predict the springback of sandwich sheets [20].

In this study, FMLC specimens were prepared using the layering method. The samples contained two aluminum sheets as the upper and lower layers, and the middle layer was considered Kevlar, carbon, and glass fiber material oriented at 0°, 90°, and ±45° angles. The springback was measured experimentally, and the test results were compared with numerical analysis outcomes, and three regression models were presented to predict the springback of this type of FML.

2. Materials and Methods

2.1. Preparing surface and making composite samples

In this study, prior to layering and creating a composite, the surfaces of the aluminum sheets were cleaned with acetone to enhance adhesion. The sheets were then treated with sodium hydroxide and rinsed with distilled water. Following this, the aluminum sheets were immersed in a sodium dichromate and sulfuric acid solution (based on ASTM D2647 standards) and subsequently rinsed with distilled water. The specimens were made using Al1050 aluminum sheets with a thickness of 1 mm, 75 g/m^2 Kevlar fiber (0.1 mm thick), 92 g/m^2 carbon fiber (0.1 mm thick), 150 g/m^2 glass fiber (0.1 mm thick), epoxy resin (R 505), and hardener (H 513). The samples were prepared in three layers. The middle layer made of Kevlar, carbon, and glass was placed between aluminum layers oriented at ±45° and 0°, 90° angles (Figs. 1 and 2). To analyze the finite element properties and determine the characteristics of metal fiber composite, tensile tests were conducted on composite samples at ±45° and 0°, 90° angles based on the ASTM D3039 standard using Santam (STM-600) set in a speed of 1 mm/min [21]. The stress and strain curves of the FMLCs are depicted in Fig. 3. The results indicated that the samples with fibers at 0°, 90° angles exhibited the highest tensile resistance [22, 23].

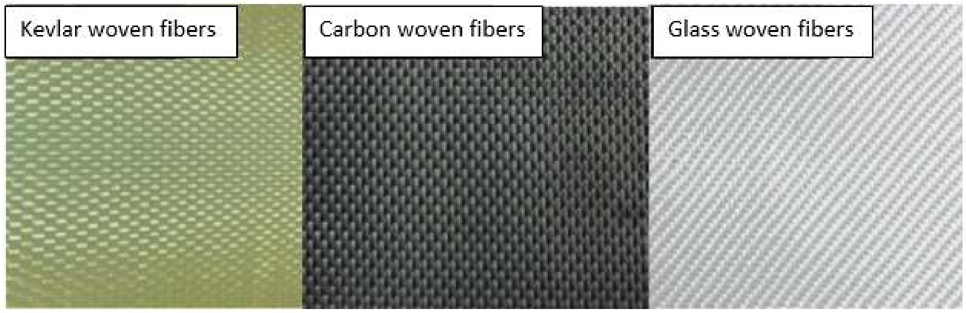

Fig. 1. Types of woven fibers used in the fabrication of FMLCs.

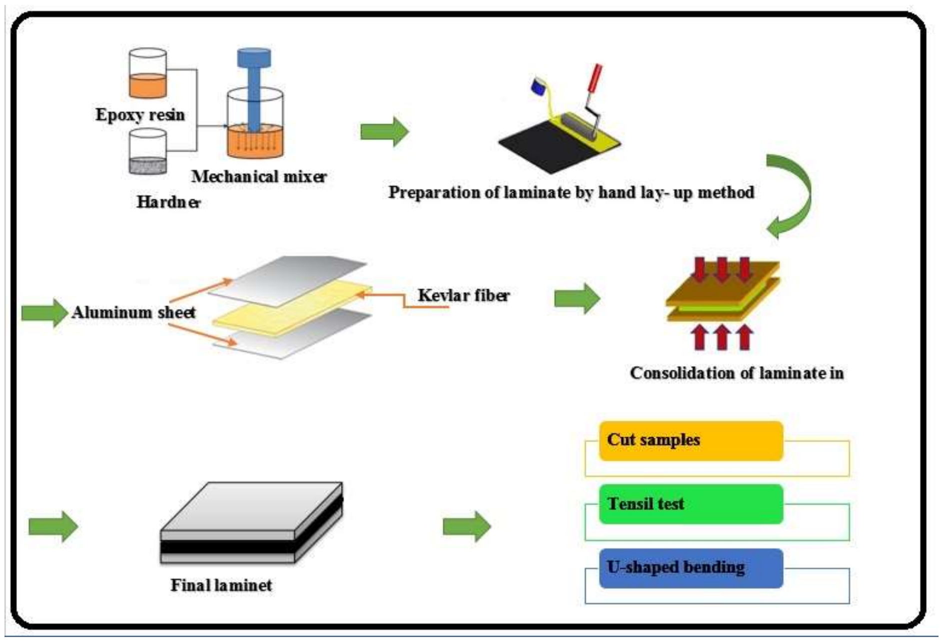

Fig. 2. Schematic representation of the steps involved in the study.

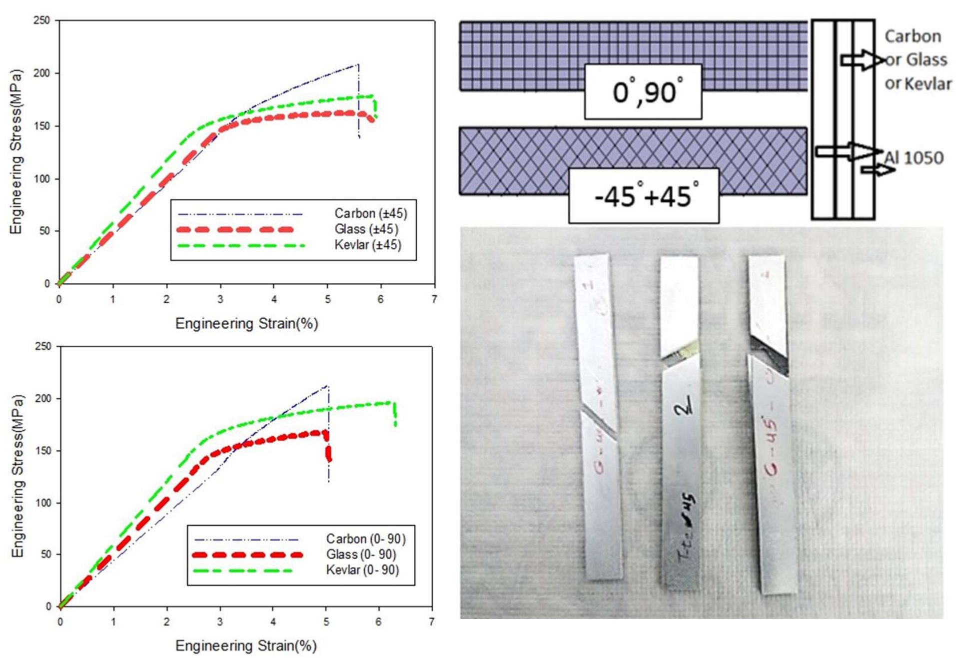

Fig. 3. Engineering stress-strain curve of the composite specimens.

2.2. Taguchi method

The Taguchi method is a widely recognized approach for quality improvement aiming to optimize parameters to minimize variation and increase consistency in the outcomes. Unlike conventional quality engineering methods, the Taguchi approach focuses on quality design rather than inspection and quality control during or after production [24]. This study seeks to identify the factors that have the greatest impact on the springback process of multi-layered fiber metal composite panels. This approach not only reduces the number of required tests but also improves economic efficiency through optimization.

In this study, three factors were considered:

- **Factor A**: Fiber angle (ϴ) with two levels: ±45˚ and 0˚, 90˚.
- **Factor B**: Punch radius (R_P) with three levels: 5 mm, 7 mm, and 9 mm.
- **Factor C**: Punch speed (V) with three levels: 50 mm/s, 60 mm/s, and 70 mm/s.

These factors are summarized in Table 1. The Taguchi design was carried out using Minitab software for FMLs made of Kevlar, carbon, and glass materials, resulting in a total of 54 tests.

Table 1. Factor level and tests configuration based on the Taguchi method for Kevlar woven fibers

Test \ Factor level	A	B	C	Test \ Factor level	A	B	C
1	1	1	1	10	2	1	1
2	1	1	2	11	2	1	2
3	1	1	3	12	2	1	3
4	1	2	1	13	2	2	1
5	1	2	2	14	2	2	2
6	1	2	3	15	2	2	3
7	1	3	1	16	2	3	1
8	1	3	2	17	2	3	2
9	1	3	3	18	2	3	3

2.3. Abaqus simulation

As shown in Fig. 4, finite element simulations were performed using Simulia Abaqus 2018. The composite sheet was modeled as a 3D deformable object, while the die and punch were modeled as discrete rigid 3D shapes. The discrete rigid molding method was selected for its simplicity and its ability to achieve more precise results. Dynamic Explicit was chosen as the type of analysis, with the time interval set at 1, 1.2, and 1.4. The impact between the punch, sheet, and die was considered to be frictionless. The mesh type was structured with hexagonal elements, with a total of 6400 elements. The mesh convergence diagram is shown in Fig. 5. The die radius (Rd) was kept constant at 10 mm, and the springback of the samples was determined for different punch radii and speeds.

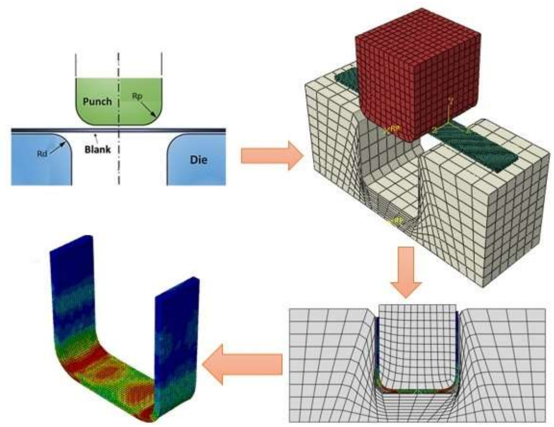

Fig. 4. Schematic diagram of the U-bending die setup.

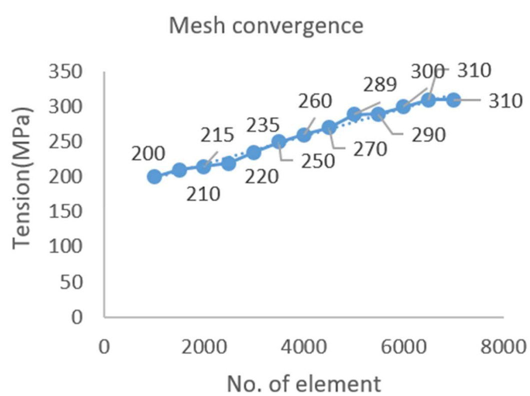

Fig. 5. Mesh convergence diagram.

2.4. Experimental procedure

The FML composite samples were cut into pieces measuring 160×20 mm using a water jet machine, according to the ASTM D2651 standard. Punches with radii of 5 mm, 7 mm, and 9 mm were also prepared [19, 25].

In bending tests, friction is a critical factor. Based on the experimental results, it was observed that samples with better dimensional accuracy were obtained when friction was eliminated. As a result, oil was used during the practical tests, and the friction force was fully controlled. Fig. 6 shows the specimens that were bent by the friction force. To conduct the stretch bending test, the die was installed on the Santam (STM-600) machine. After installation, the samples underwent the bending operation. Fig. 7 shows the stretch die installed on the Santam (STM-600) universal testing machine.

2.5. Springback angle

Springback is the amount of elastic distortion a material undergoes before becoming permanently deformed or shaped. It represents the elastic tolerance inherent in every material and affects the final shape of a workpiece. In ductile materials, springback is lower compared to hard metals, depending on the material's modulus of elasticity. The amount of springback increases with greater yield strength or the material's strain-hardening tendency. Both cold working and heat treatment can increase the amount of springback in a material. For instance, low-strength steel exhibits smaller springback compared to high-strength steel, while aluminum exhibits springback two or three times higher than steel. Springback occurs in all formed or bent-up parts once the forming pressure is released and the punch is withdrawn. The material, previously held in a predetermined arrangement by these elements, is suddenly free from outside restrictions and immediately attempts to return to its original shape and form [26]. In this study, both experimental and numerical tests were performed on the specimens to evaluate the springback behavior.

3. Results and Discussion

The Taguchi analysis method enables the separate analysis of each factor influencing springback while conducting only a limited number of tests. Fig. 8 illustrates the factors with the greatest impact on the springback process. Based on these diagrams, it is evident that the punch radius has a more significant effect on springback than the other factors. Using variance analysis conducted with Minitab software, the criticality and effects of the selected factors were determined. For instance, the results indicate that the sample from Test 10, with the least springback (0.5), is in the optimal situation for Kevlar fibers. The diagrams in Fig. 8 demonstrate that selecting level 2 for factor (A), level 1 for factor (B), and level 1 for factor (C) yields the minimum springback, which corresponds to Test 10 in Table 1. Similar results were observed for carbon fibers and glass fibers.

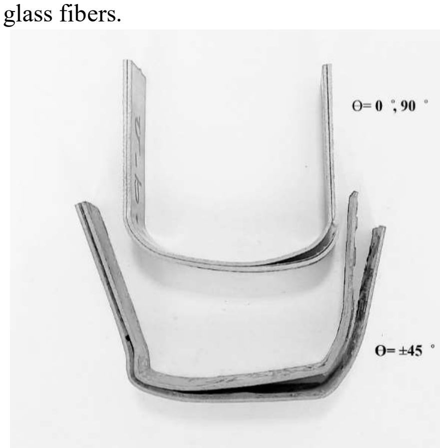

Fig. 6. Damaged samples caused by friction between the FMLs and the die.

Fig. 7. Bending process using the Santam STM-600 Machine.

Fig. 8. Diagrams showing the effect of each factor on springback using Minitab.

3.1. The effect of punch radius parameters on springback of FML

Three types of punches with corner radii of 5, 7, and 9 mm were prepared. A radius greater than 9 mm would cause spring-go, while a radius less than 5 mm would lead to crushing. According to the Taguchi method, the springback result for the samples indicates that the punch radius factor has the most significant impact on the springback of fiber metal composites. A reduction in punch radius leads to a decrease in springback due to the reduction of residual stress in the bending area. As the bending radius increases, the residual stress area expands, leading to increased negative tension. In aluminum sheets, a smaller punch radius causes more plastic deformation and reduces the springback rate. According to Fig. 9, this relationship can be explained mathematically. According to Eq. (1), α_S has a direct relationship with R_P. In other words, as α_S increases, the value of R_P also increases [27].

Figs. 10, 11, and 12 demonstrate that, at a constant punch speed, springback increases as the punch radius increases. This trend is also reflected in Table 2. These results are consistent with the findings of Young's research [13].

$$W = \alpha_P\left(R_P + \frac{t}{2}\right) = \alpha_S\left(R_S + \frac{t}{2}\right) \rightarrow \frac{\alpha_S}{\alpha_P} = \frac{R_P + \frac{t}{2}}{R_S + \frac{t}{2}} \quad (1)$$

R_P = Bending radius or punch radius
R_S = Springback radius
t = Specimen thickness
α_P = Bending angle
α_S = Springback angle
W = Length wise portion

3.2. The effect of loading speed on springback

To study springback, the speeds of 50, 60, and 70 mm/s were considered. A speed higher than 70 mm/s would cause the samples to break due to the high strain rate, and speeds lower than 50 mm/s also caused spring-go. Table 2 shows that increasing punch speed results in an accelerated springback for the same punch radius. The loading speed of the punch on aluminum sheets contributes to an increase in springback. As punch speed increases, the crushing speed also increases, leading to a buildup of negative stress. Residual stresses are the primary cause of springback. The transverse residual stress distributions of sheet parts formed by bending will affect the loading capacity or the strength of the part.

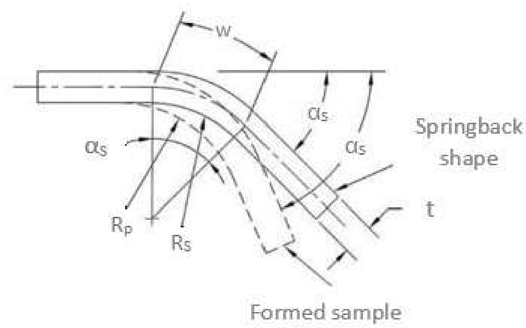

Fig. 9. Springback parameters.

Fig. 10. Springback of experimental samples with fiber angle ±45˚ and V=60 mm/s.

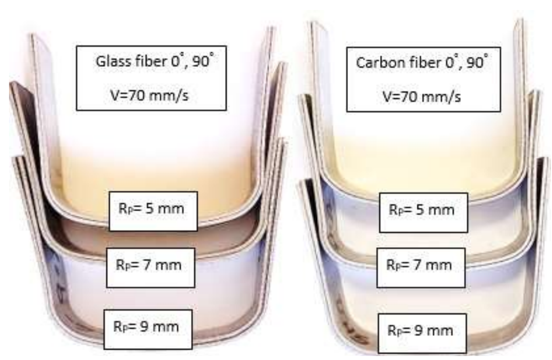

Fig. 11. Springback of experimental samples with fiber angle 0˚, 90˚ and V=70 mm/s.

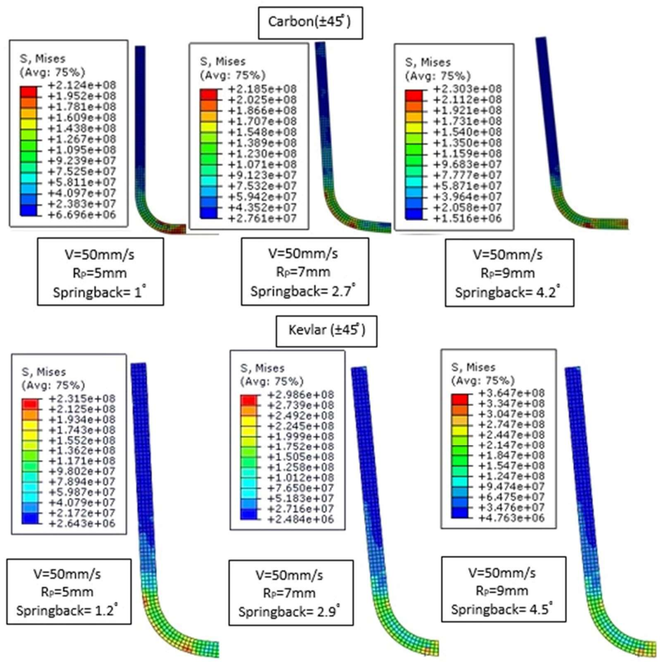

Fig. 12. The effect of punch radius on springback with fiber angle ±45˚.

Table 2. Effect of R_P, V, and Θ on springback in FMLs reinforced with Kevlar, carbon and glass

Fiber angle	V (mm/s)	R_P (mm)	Kevlar springback (simulation)	Kevlar springback (experimental)	Carbon springback (simulation)	Carbon springback (experimental)	Glass springback (simulation)	Glass springback (experimental)
		R_P=5	1.2	1.63	1	1.5	2	2.5
±45˚	50	R_P=7	2.9	3.4	2.7	3.1	2.9	3.9
		R_P=9	4.5	5.01	4.2	4.01	4.4	5.8
		R_P=5	2.5	3	2.2	2.9	3	3.5
±45˚	60	R_P=7	4.9	5.5	4.5	5.2	5.2	6.5
		R_P=9	5.42	6	5	5.5	6	7
		R_P=5	3.7	4.2	3.2	4	4	4.5
±45˚	70	R_P=7	5.8	6.2	5.2	5.9	6.1	6.8
		R_P=9	6.8	7.1	6.1	6.5	7.1	7.9
		R_P=5	0.2	0.5	0.01	0.1	0.5	1
0˚, 90˚	50	R_P=7	1.5	2.01	1.2	2	2.1	2.9
		R_P=9	2.94	3.11	2.7	2.8	3	3.8
		R_P=5	1	1.6	1	1.3	1.4	2
0˚, 90˚	60	R_P=7	1.72	2.03	1.5	1.9	1.9	2.5
		R_P=9	3.05	3.4	2.9	3	3.5	4
		R_P=5	1.29	1.83	1.2	1.7	2.2	2.83
0˚, 90˚	70	R_P=7	2.87	3.45	2.7	3	3.5	4.2
		R_P=9	3.5	4	3.1	3.5	4.2	5.1

After unloading, the tension side of the bent specimen would have a significant compressive residual stress at the outer surface, while there would be a residual tensile stress at the inner surface [20]. As shown in Table 2, for all three fiber types at a constant punch radius, springback increases as punch speed increases. Comparing the values in the tables, it can be observed that the lowest springback occurs for carbon fibers, while the highest springback is seen in glass fibers. These findings are consistent with Young's research [13].

3.3. The effect of fibers angle ±45˚ and 0˚, 90˚ on springback

In this study, samples were reinforced with carbon, Kevlar and glass fibers of identical dimensions. The specimens were made with fiber angles of (±45˚) and (0˚, 90˚). After conducting the bending test, the samples were removed from the die, and their springbacks were measured using checker paper. The results are shown in

Table 2. The experimental data and simulation results indicated that in the case of fiber angles of 0˚, 90˚, the springback was less than the angle of ±45˚because at this angle the residual stresses are lower and the elastic resistance of fiber at 0˚, 90˚ is lower than at ±45˚. Because 0˚, 90˚fibers are created exactly in the direction of bending, they show more resistance against springback [21]. The results align with the findings of Keipour et al. [19]. As can be seen in Table 2, the simulated springback angles are slightly smaller than the experimental values [20].

3.4. Regression models

According to the results, three regression models were provided to predict springback. SPSS software was used to derive these models. Eqs. (2), (3), and (4) predict the springback of FMLs reinforced with Kevlar, carbon and glass fibers, respectively.

$$S_{Pr}=-3.31028+0.660833\times Rp+0.092667\times V-0.04899\times \Theta \quad (2)$$

$$S_{Pr}=-3.13736+0.57541\times Rp+0.092417\times V-0.04768\times \Theta \quad (3)$$

$$S_{Pr}=-3.14431+0.71958\times Rp+0.09525\times V-0.04956\times \Theta \quad (4)$$

In these equations, S_{Pr}, Θ, V, and R_P represent springback, fiber angle, punch speed, and punch radius, respectively. The correlation coefficients of the regression models between the simulation and predicted values for Kevlar, carbon and glass fibers are 0.97049, 0.96154, and 0.96682, respectively. After developing the regression models, 24 simulation tests were performed. The springback values obtained from the simulation results were compared with the results estimated by the regression models. In Tables 3, 4, and 5, the springback values estimated by the regression model are compared with the simulation values. The analysis showed that the mean errors of the regression models in estimating springback were 9.31, 8.05, and 6.06%, respectively.

Table 3. Accuracy check of the regression model for FMLs reinforced with Kevlar

Kevlar springback					
R_p	V	Θ	S_{Pr} (simulation)	S_{Pr} (regression)	Error (%)
11	90	30	8.9	10.82926	17.81525
13	70	45	8.3	9.562778	13.20514
17	110	60	16.2	15.17796	6.308871
11	70	45	8.9	8.241111	7.403246
17	90	60	12.1	13.32463	9.190722
17	110	30	17.9	16.64759	6.996689
11	70	90	6.5	6.036667	7.128205
13	110	60	13.4	12.53463	6.457988
				Mean error	**9.31**

Table 4. Accuracy check of the regression model for FMLs reinforced with carbon

Carbon springback					
R_p	V	Θ	S_{Pr} (simulation)	S_{Pr} (regression)	Error (%)
11	90	30	8.5	10.07935	15.66916
13	70	45	8	8.666677	7.692297
17	110	60	12.5	13.94981	10.39305
11	70	45	8	7.515833	6.441895
17	90	60	12.5	12.10148	3.293090
17	110	30	14.8	15.38019	3.772255
11	70	90	6	5.370278	11.72603
13	110	60	13	13.74602	5.429303
				Mean error	**8.05**

Table 5. Accuracy check of the regression model for FMLs reinforced with glass

Glass springback					
R_p	V	Θ	S_{Pr} (simulation)	S_{Pr} (regression)	Error (%)
11	90	30	10.5	11.85698	11.44430
13	70	45	11	10.64778	3.307944
17	110	60	17.2	16.59278	3.659440
11	70	45	8.5	9.208611	7.694980
17	90	60	13.8	14.68778	6.043832
17	110	30	17.6	18.07944	2.651695
11	70	90	6.5	6.978611	6.858109
13	110	60	14.8	15.89489	6.883100
				Mean error	**6.06**

4. Conclusion

This study investigated the effects of punch radius, fiber angle, and loading speed on the springback behavior of FML sheets in the stretch U-bending process, both experimentally and numerically. Al1050 was reinforced with Kevlar, carbon, and glass woven fibers. To assess the impact and sensitivity of these factors on springback, the Taguchi's method was applied. A comparison of the simulation results and experimental tests showed a strong agreement. The findings revealed that the punch radius factor has the greatest effect on the springback of FMLs. As both the punch radius and punch speed increase, the springback also increases. Additionally, the composite sample with fiber angles of (0°, 90°) exhibited the lowest springback, compared to the (±45°) fibers. Based on experimental and numerical springback values, three regression models were developed. The models were evaluated based on the numerical values and the mean errors for FMLs reinforced with Kevlar, carbon, and glass were found to be 9.31%, 8.05%, and 6.06%, respectively.

Conflict of interest

The authors have no conflict of interests to declare.

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