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Springback behavior of fiber metal laminate (FML) composites in press brake forming process

Fiber metal tabakalı kompozitlerin preste şekillendirilmesinde geri yaylanma davranışı

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Abstract

The brake forming process is suitable for producing fiber metal laminate (FML) composites. However, the springback that occurs during braking causes severe problems in the final dimensional tolerance of the composite laminate. In this study, the springback behavior of fiber metal laminate (FML) composites in the v-shaped brake-forming process were experimentally investigated. In FML composites, 6061-T6 Aluminum was used on the outer surfaces, and carbon, glass, carbon/glass, and aramid fiber-reinforced epoxy composite plates were used in the inner layers. The effects of bending angle and die width parameters on springback behavior in the v-shaped brake-forming process were examined. Forming processes were carried out with bending angles of 140°, 150°, and 160° and two different mold widths: 16 and 20 mm. As a result of experiments, the highest springback was observed in the aluminum-carbon fiber-aluminum composite plate with 15.1° and the lowest springback was observed in the aluminum-glass/carbon fiber-aluminum composite plate with 0.4°. The highest spring-go was obtained in the aluminum-aramid fiber-aluminum composite plate with -1.7°, while the lowest spring-go was obtained in the aluminum-glass fiber-aluminum composite plate with -0.3°.

Keywords: FML, Springback, Spring-go, Press brake forming

Öz

Abkant preste şekillendirme prosesi, fiber metal tabakalı (FML) kompozitlerin üretimi için uygun bir yöntemdir. Ancak şekillendirme sırasında oluşan geri yaylanma, kompozit plakanın son boyut toleransında ciddi sorunlara neden olmaktadır. Bu çalışmada, fiber metal tabakalı (FML) kompozitlerin abkant preste v-şekilli şekillendirme prosesindeki geri yaylanma davranışı deneysel olarak incelenmiştir. FML kompozitlerde dış yüzeylerde 6061-T6 Alüminyum, iç katmanlarda ise karbon, cam, karbon/cam ve aramid elyaf takviyeli epoksi kompozit levhalar kullanılmıştır. V-şekilli abkant pres şekillendirme prosesinde bükme açısı ve kalıp genişliği parametrelerinin geri yaylanma davranışına etkileri incelenmiştir. Şekillendirme prosesleri 140°, 150° ve 160° bükme açıları ve 16 ve 20 mm olmak üzere iki farklı kalıp genişliği ile gerçekleştirilmiştir. Deneyler sonucunda en yüksek geri yaylanma 15,1° ile alüminyum-karbon fiber-alüminyum kompozit levhada, en düşük geri yaylanma ise 0,4° ile alüminyum-cam/karbon fiber-alüminyum kompozit levhada gözlenmiştir. En yüksek geri yaylanma -1,7° ile alüminyum-aramid fiber-alüminyum kompozit levhada elde edilirken, en düşük geri yaylanma -0,3° ile alüminyum-cam fiber-alüminyum kompozit levhada elde edilmiştir.

Anahtar kelimeler: FML, Geri yaylanma, İleri yaylanma, Pres şekillendirme

1 Introduction

Composite materials are one of the materials researched and developed as alternative materials to existing materials used in many sectors such as the defense industry, aviation industry, automotive industry, space technologies, and energy. Thanks to composite materials created by combining different materials on a macroscopic scale, properties such as lightness, high strength, fatigue life, rigidity, thermal conductivity, wear resistance, and corrosion resistance can be improved. FML (Fiber metal laminate) systems are a hybrid material consisting of alternating layers of metal and fiber-reinforced polymer composite [1]. The development of FML composites began in the 1970s. These materials are based on combining the two materials to eliminate the harmful properties such as low fatigue strength observed in metals such as aluminum and poor impact strength and residual stress observed in carbon fibers. Although many different types of metals are used in producing FML composites, aluminum and titanium are especially preferred due to their lightness and high strength. Aluminum is more widely used due to its availability and ease of processing. In addition, almost all types of fiber materials, such as glass, carbon, or aramid, are used in FML composite production. Commonly used combinations are glass fiber-aluminum laminated composite (GLARE), aramid fiber-aluminum laminated composite (ARALL), and carbon fiber-aluminum laminated composite (CARALL) composites. Their sandwich nature and the combination of different materials afford them good impact and fatigue properties and superior specific properties such as strength to weight and stiffness to weight [2]–[3]. Fiber metal laminated composites are hybrid structures composed of different metal sheets (usually aluminum) and fiber-reinforced polymer/epoxy matrix composites such as carbon, glass, or aramid [4]–[7]. Today, it is widely used in the automobile, aircraft, aerospace, and defense industries. As the usage areas of FML composite sheets increase, the need to shape sandwich composite sheets according to where they are used has emerged [8]–[10]. The

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springback problem is one of the biggest problems encountered in forming sheet metal materials; it would affect sandwich composite sheets, which are preferred due to their high performance and resistance to environmental effects [11]–[13]. In the bending process, when the force applied to the material is removed, compressive stresses occur in the inner deformation zone, and tensile stresses occur in the outer deformation zone. When the force applied to the material is removed, the material tries to return to its initial state due to these stresses, and this causes the bent material to stretch and open. This phenomenon occurring in the material is called springback [14]. Springback, which generally occurs after bending in sheet metal materials, removes the material from the final form and causes the desired dimensions to change [9], [15]–[17].

Stress and shape changes occurring in the bent material cross-section generally depend on the type of material, material thickness, bending angle, tip radius of the punch, bending force, ironing time, bending speed, and the gap between the female mold and the punch [18]–[26].

Kim and his colleagues experimentally investigated the amount of springback that occurs from shaping composite sheets, which they prepared by placing glass fiber between Al2024 sheets in a 90° V bending mold. This study examined the effects of punch radius, bending speed, and temperature parameters on springback. As a result of the experiments, it was determined that the amount of springback increased as the punch radius increased due to plastic deformation. It has been observed that springback increases slightly with increasing bending speed. Additionally, a decrease in the amount of springback occurring in composite sheets bent at higher temperatures has been detected [27]. Uriya and his colleagues investigated the springback angles in carbon fiber-reinforced plastic sheets after applying a 90° V bending process in hot and cold environments. They produced carbon fiber-reinforced plastic sheets by combining carbon fibers' lower and upper surfaces with different alignments produced by the prepreg method with A2024 sheet metal, which they call dummy sheets. In the experiments, carbon fiber-reinforced plastic sheets were shaped in a 90° V bending mold at temperatures of 20°C, 100°C, and 200°C. In the experiments, it was determined that springback decreased with increasing bending temperature. In addition, it was stated that deformation and tears occurred on the sample surface when bending the test samples consisting only of carbon fiber without using A2024 [19]. Parsa et al. investigated the effect of punch radius on springback in the shaping of metal/polymer/metal layer sandwich materials with a V-bending die, using experimental and finite element methods. Sandwich materials created using aluminum A3105 as metal and polypropylene as polymer were shaped in a 90° V bending mold. Sandwich samples produced in different thicknesses were bent using 4, 8, and 12 mm punch radii. According to the data obtained from the experiments, it was determined that the springback in the material increased as the punch radius increased. Additionally, it has been stated that the amount of springback decreases at all punch radii as the sandwich sheet thickness increases [28]. Choi and his colleagues studied the experimental determination of the springback that occurs when hybrid composites are shaped in a 90° V bending mold. In the study, CFRP/CR340 hybrid composites were used. The effects of parameters such as punch pressure, punch radius, number of CFRP layers, and CR340 rolling direction on springback were investigated in the experiments. In the experiments, the layers of CFRP were selected as 5, 10, and 20 layers. While 0° and 90° were used as the rolling directions of CR340 sheets, the punch radius values were determined as 2, 5, and 8 mm. The experiments determined that while springback was observed in CFRP/CR340 composite materials, there was forward stretching in CR340/CFRP composite materials. In CFRP/CR340 composite materials, it has been observed that springback decreases as the number of layers of CFRP increases. In CR340/CFRP composite materials, it has been determined that forward flexibility decreases as the number of layers of CFRP increases. Additionally, it has been stated that springback in hybrid composites changes when the rolling direction changes [29]. Yanagimoto and Ikeuchi experimentally investigated the shaping of carbon fiber-reinforced plastic sheets by 90° V bending. They produced carbon fiber-reinforced plastic sheets by combining soft sheets on the upper and lower surfaces of carbon fibers in 0°, 45°, and 90° alignments produced using the prepreg method. It has been stated that tearing occurs during the bending of composite sheets at room temperature. It has been determined that these tears are caused by breaking carbon fibers running perpendicular to the sharp corner of the punch. It was observed that carbon fiber-reinforced plastic sheets could be bent when the mold was heated to 100 °C [30].

Hahn et al. investigated the V-die bending of a carbon-fiber-reinforced thermoplastic laminate bonded to thin cover layers made of micro-alloyed steel. Different forming temperatures, dwell times, and punch radii were studied to determine suitable process parameters on the springback/negative springback of the fiber metal laminate (FML) [31]. Wang et al. investigated the bending behavior of carbon fiber-reinforced plastic (CFRP)/Al laminates. They studied the influences of fiber direction, metal thickness ratio, and temperature on springback. Results showed that the fiber direction significantly influences the failure mode and springback of the laminates. The change in springback rate is inevident below 150 °C, and the delamination between fiber and metal layers occurs near 200 °C [32]. With the increase in sandwich composite panels, the need to shape them according to where they are used has also emerged. For this reason, the shaping ability of sandwich composite panels has been investigated. The experimental study investigated how the springback problem, one of the biggest problems encountered in shaping metal sheet materials, will affect sandwich composite panels, which are preferred due to their high performance and resistance to environmental effects. Material properties such as corrosion resistance, lightness, high fatigue resistance, and high strength of carbon fiber materials have reduced the demand for metals. In addition to these superior properties of carbon fiber, its low formability is a disadvantage. Carbon fiber-metal hybrid composites have been developed to overcome this disadvantage. For example, carbon fiber-aluminum hybrid composite structures are 56% lighter than an equivalent aluminum material and provide higher performance in terms of hardness and strength [33].

This study investigated springback characteristics of fiber metal layer composite (FML) composites in the brake forming process. FML composites were created by placing fiber composites between aluminum plates. Springback behaviors were experimentally examined by performing the process at different bending angles (140°, 150°, and 160°) and mold widths (16 mm and 20 mm). The forming and springback behaviors of composite plates were experimentally examined using the brake-forming process.

2 Experimental study

This study investigated the springback behavior of fiber metal laminate (FML) composites with a v-shaped brake-forming process. Aluminum plate is used on the outer surfaces of the FML composite, and carbon, glass, carbon-glass, and aramid fiber-reinforced epoxy plates are used on the inner layers. The aluminum plate was used in two thicknesses: 1 and 1.5 mm. Fiber plates are produced in 1 and 1.5 mm thickness, compatible with aluminum thickness. Therefore, the total thickness of FML composites is 3 and 4.5 mm. In forming FML composites by the v-shaped brake forming process, the effects of material type, thickness, bending angle parameters, and mold width on springback and spring-go were investigated. A schematic view of the FML composite is given in Figure 1.

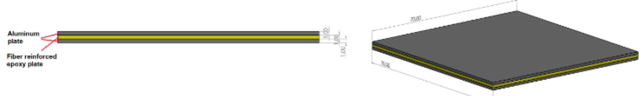

Figure 1. Schematic view of FML composite.

The metal plate used in the study is an Al6061-T6 alloy. These materials are used mainly in the aircraft, defense, pipe, boiler, and wagon industries. The mechanical and chemical properties of Al6061-T6 alloy are given in Tables 1 and 2 below.

Table 1. Chemical composition of Al6061-T6 alloy.

Element	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
%	0.4-0.8	0.7	0.15-0.4	0.15	0.8-1.2	0.04-0.35	0.25	0.15	Balance

Table 2. Mechanical properties of Al6061-T6.

Material	Tensile Strength (MPa)	Yield Strength (MPa)	Elongation at break %	Brinell Hardness (500 g load, 10 mm ball)	Shear Strength (MPa)
Al6061-T6	310	276	12	95	20

Aluminum plates are 1 mm and 1.5 mm thick. The experiments were carried out with specimens it is measuring 70x70 mm. Carbon fiber, carbon-glass fiber, glass fiber, and aramid fiber reinforced epoxy plates of the same thickness (1 mm and 1.5 mm) and dimensions as the aluminum plate thickness used in the middle part of the sandwich structure were used. Carbon fiber is plain woven, and its density is 200 g.mm-2. It is carbon-glass fiber, twill woven, and its density is 220 g.mm-2. Aramid fiber is a twill weave, and its density is 170 g.mm-2. Glass fiber is a twill woven with 280 g.mm-2. The modulus of elasticity of carbon, glass, and aramid fiber fabric is 285 GPa, 72.5 GPa, and 131 GPa. The tensile strength of carbon, glass, and aramid fiber fabric are 6350 MPa, 3450 MPa, and 4100 MPa, respectively.
Fiber composite sheets were manufactured using the vacuum bagging method. The processes applied during the manufacturing phase are as follows. A separator called SW-6 was applied to the cleaned 10 mm thick glass sheet, and after waiting for it to dry, the surface was polished with a cloth. The same process was then repeated using Polimax EN. A frame was created on the glass sheet with vacuum paste in a way that would be 5 cm larger than the dimensions of the part to be manufactured. The liquid separator was applied inside this frame so that the entire surface would not remain dry, and it was waited to dry. A plate of aluminum sheets was placed in the middle of the frame, and fiber fabrics were placed on it regularly. Separator peel-ply fabric was laid on the fiber fabrics. A resin flow network was laid on it. The resin and vacuum lines were created by wrapping the resin flow network outside the spiral hose. Separator peel-ply fabric was stapled to the fiber fabrics. The vacuum line was connected to the vacuum tank with a 12 mm diameter hose. The resin line was extended with the help of the hose. The vacuum film was glued to the sheet by giving pot heights from different points. The vacuum line valve was opened, and the air inside the plate created at -0.6 bar pressure was removed. A homogeneous mixture was prepared using 60% resin and 1.4-1 hardener based on the weight of the fabric used. Laminating resin MGS L160 and hardener L160 were used as resin and hardener. The mixture was mixed until it became homogeneous. The resin was impregnated into the plate created from the resin line. It was waited for 12 hours while the vacuum line remained active. After waiting for 12 hours, the plate was removed from the system, leveled, and made ready. Aluminum and composite plates were glued to each other with Araldite 2011 epoxy adhesive. The resulting product was made ready for testing and kept under pressure in a hydraulic press for 24 hours. Bending test samples measuring 70 x 70 mm were cut from the created composite plate.

Images of the manufacturing phase are given in Figure 2.

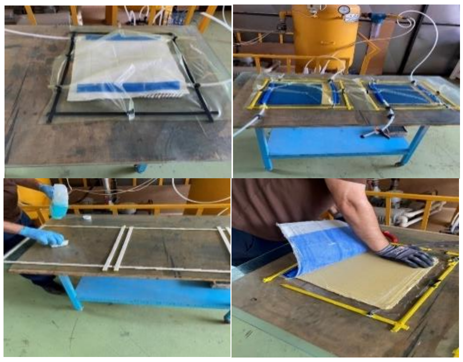

Figure 2. Composite material manufacturing stages.

V-bending experiments were conducted with Dener Brand Puma XL 30135 model CNC press brake. The image of the press machine is given in Figure 3.

Figure 3. Press brake machine.

Each sample was bent at 140^0, 150^0, and 160^0 bending angles in V16 and V20 molds with 16 mm and 20 mm mold widths. Pressure forces applied by the press brake to the samples: 4.6 tons for 3 mm thick material and 6.9 tons for 4.5 mm thick material. Bending tests were performed according to ASTM d790 standards. In experimental studies, each experiment was applied three times. Average test results were taken as the basis. A schematic view of the mold is given in Figure 4. The components of the test specimen and test parameters are shown in Table 3.

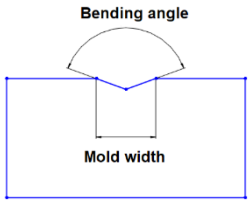

Figure 4. Schematic view of mold.

Table 3. Components of test specimen and test parameters.

<table>
<tr><th colspan="3">Components of test specimens</th><th colspan="2">Test parameters</th></tr>
<tr><th>Bottom plate</th><th>Middle Plate</th><th>Top plate</th><th>Bending angle</th><th>Mold width</th></tr>
<tr><td rowspan="4">1 mm Al</td><td>1 mm carbon fiber</td><td rowspan="4">1 mm Al</td><td rowspan="4">140^0
150^0
160^0</td><td rowspan="4">16 mm
20 mm</td></tr>
<tr><td>1 mm carbon-glass fiber</td></tr>
<tr><td>1 mm glass fiber</td></tr>
<tr><td>1 mm aramid fiber</td></tr>
<tr><td rowspan="4">1.5 mm Al</td><td>1.5 mm carbon fiber</td><td rowspan="4">1.5 mm Al</td><td rowspan="4">140^0
150^0
160^0</td><td rowspan="4">16 mm
20 mm</td></tr>
<tr><td>1.5 mm carbon-glass fiber</td></tr>
<tr><td>1.5 mm glass fiber</td></tr>
<tr><td>1.5 mm aramid fiber</td></tr>
</table>

As a result of the v-shaped brake-forming process, springback, and spring-go amounts were measured with a digital protractor. Images of brake forming and springback measurement are given in Figure 5.

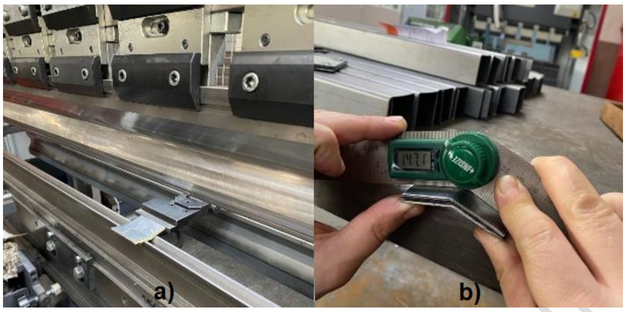

Figure 5. Images during and after the experiment: a) Forming in the press brake and b) springback measurement after bending.

The schematic image of the springback calculation is given in Figure 6.

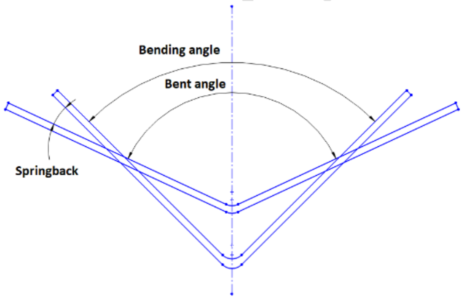

Figure 6. Schematic view of springback calculation.

3 Experimental results

The v-shaped brake forming test results of FML composites performed at different bending angles and mold widths are given in Table 4. In the results obtained, if the springback angle measurement result is more significant than the tested, it is seen that the material is springing back; if it is smaller, it is spring-go. In Table 4, springback was observed in FML composites using carbon and carbon-glass fiber and spring-go using glass and aramid fiber. It was observed that springback decreased as the specimen thickness increased. The decrease in springback as the thickness increases is a situation seen in most studies in the literature [29], [34]. It was determined that springback or spring-go increased when the mold width increased. It was determined that springback increased when the mold width increased. When the bending angle increased, the amount of springback generally decreased in most specimens.

Graphs showing the change in springback depending on the bending angle are given in Figures 7 and 8. Error bars in the springback results in Figure 7-8. The graphs were created by calculating the averages of the springback or spring-go results of the tests repeated in this experimental study.

Table 4. Test results of fiber-metal sandwich composites made with 16 mm and 20 mm mold width.

Specimen thickness (t) (mm)	Specimen type	Die angle	Mold width: 16 mm (V16)		Mold width: 20 mm (V20)	
			Springback or spring-go angle	Springback (SB) or Spring-go (SG) type	Springback or spring-go angle	Springback (SB) or Spring-go (SG) type
3	Al-C-Al	140	13.1	SB	13.5	SB
		150	8.2	SB	8.7	SB
		160	5.4	SB	6.1	SB
	Al-G-Al	140	-0.5	SG	-0.8	SG
		150	-1	SG	-1.4	SG
		160	-0.4	SG	-0.6	SG
	Al-A-Al	140	-0.9	SG	-1.2	SG
		150	-1.2	SG	-1.7	SG
		160	-0.7	SG	-0.9	SG
	Al-CG-Al	140	2.2	SB	2.4	SB
		150	1	SB	1.8	SB
		160	0.8	SB	1.3	SB
4.5	Al-C-Al	140	13	SB	15.1	SB
		150	8.5	SB	9.8	SB
		160	5.9	SB	7	SB
	Al-G-Al	140	-0.8	SG	-1	SG
		150	-0.7	SG	-0.7	SG
		160	-0.3	SG	-0.4	SG
	Al-A-Al	140	-0.7	SG	-0.8	SG
		150	-0.9	SG	-1.2	SG
		160	-0.5	SG	-0.7	SG
	Al-CG-Al	140	1.2	SB	1.5	SB
		150	1.5	SB	1.1	SB
		160	0.4	SB	0.8	SB

A: Aluminum, C: Carbon, G: Glass, CG: Carbon-Glass, A: Aramid.

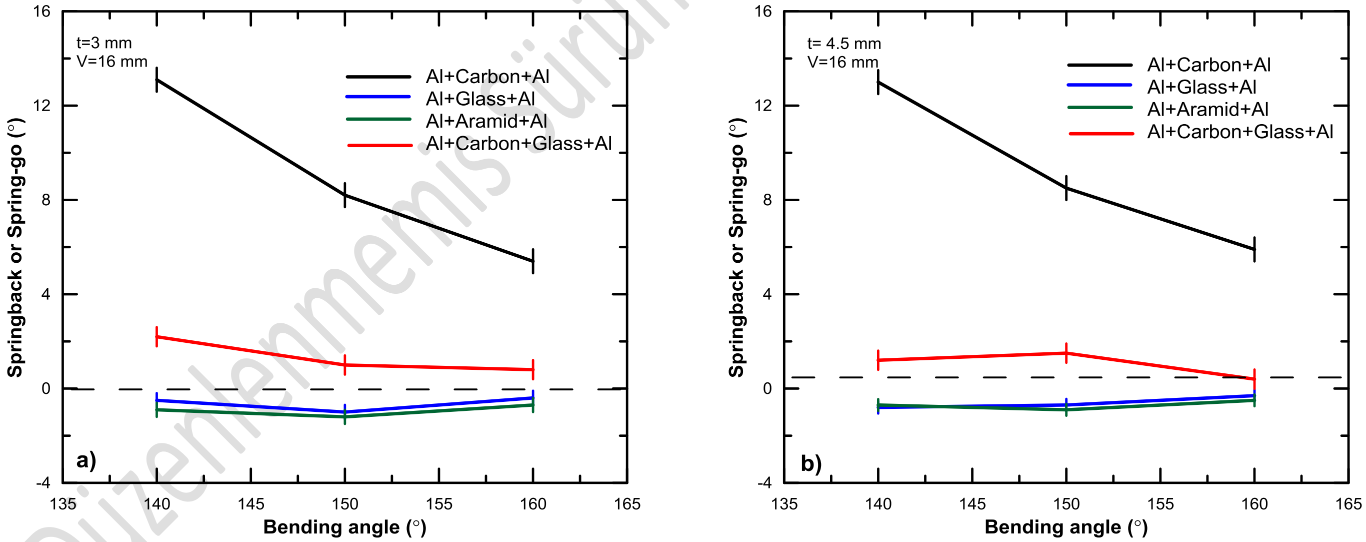

Figure 7. Springback or spring-go variation depending on bending angle for 16 mm mold width for two specimen thicknesses, a) t=3 mm, b) t=4.5 mm.

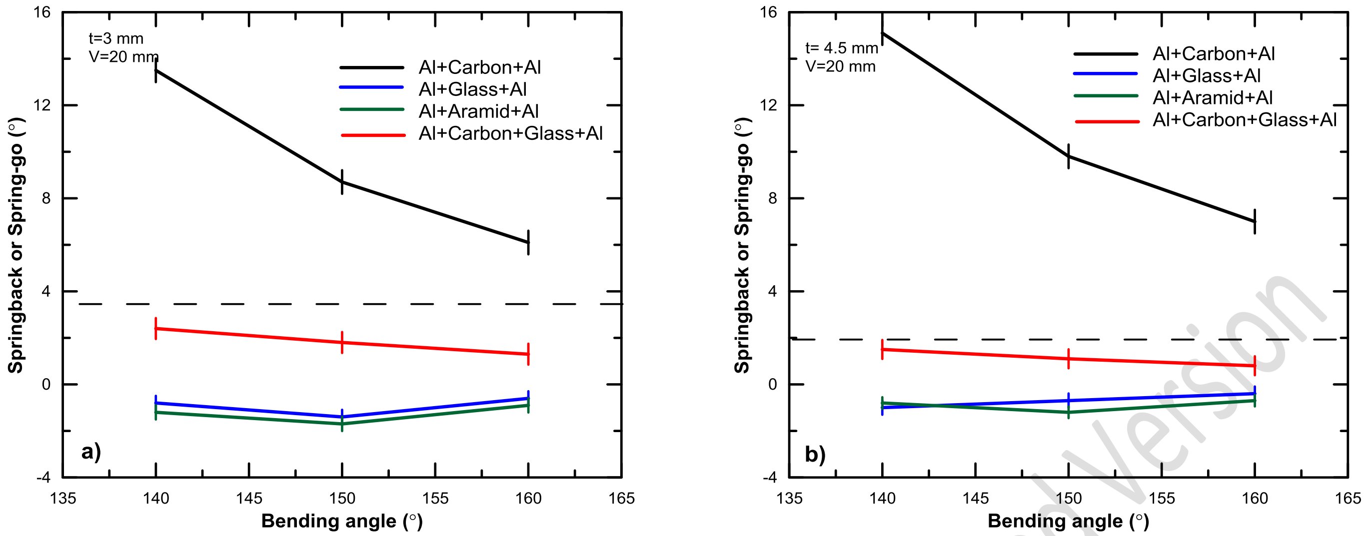

Figure 8: Springback or spring-go variation depending on bending angle for 20 mm mold width for two specimen thicknesses, a) t=3 mm, b) t=4.5 mm.

As a result of the experiments, it was observed in Figure 7 with 16 mm mold width that while springback occurred in Al+Carbon+Al (t=3 mm) specimen and Al+Carbon+Glass+ Al (t=3 mm) specimen, spring-go occurred in composite materials produced with Al+Glass+Al (t=3 mm) specimen and Al+Aramid+Al (t=3 mm) specimen. When figures are examined, springback values decrease as the bending angle increases in Al+Carbon+Al and Al+Carbon+Glass+ Al composites. In Al+Glass+Al and Al+Aramid+Al specimens, the bending angle increased from 140° to 150°, while the spring-go decreased and increased at 160°. In the Al+Glass+Al and Al+Aramid+Al (t=3 mm) samples, the springback values did not change much when the bending angle increased from 140 to 160 (Figure 7-a). In Al+Carbon+Al (t=3 mm) specimen, 13.1° springback was measured in the test performed with a 140° bending angle. When the bending angle was 150°, 8.2° springback was measured, and when it was 160°, 5.4° springback was measured. In the Al+Carbon+Glass+Al (t=3 mm) specimen, when the bending angle increased from 140 to 160, the springback value decreased from 2.2 to 0.8 (Figure- 7-a).
In the experiments (Figure 7-b) where the specimen thickness was increased to 4.5 mm for a mold width of 16 mm, it showed similar behavior to the 3 mm thick specimens. Differently, in the Al+Carbon+Glass+Al specimen, springback increased as the bending angle increased from 140 to 150, but springback decreased significantly when the bending angle increased to 160. In the Al+Aramid+Al (t=4.5 mm) specimen, -0.7° spring-go was measured in the test performed with a 140° bending angle in a 16 mm wide mold width. Spring-go was calculated as -0.9° when the bending angle was 150° and -0.5° when it was 160°(Figure 7-b).

In Al+Carbon+Al (t=3 mm) specimen in Figure 8-a, 13.5° springback was measured in the test performed with a 140° bending angle in a 20 mm wide mold width. When the bending angle was 150°, 8.7° springback was measured, and when it was 160°, 6.1° springback was measured. It has been observed that as the mold width increases, the amount of springback also increases in degrees. It has been determined that as the bending angle increases, results closer to the desired bending degree are measured.
In the specimens where the thickness of the reinforcement parts was 1.5 mm for 4.5 mm specimen thickness, the springback increased as the mold width increased. Increasing part thickness for the same mold width decreased the springback values slightly (Figure 8-b). In the Al+Aramid+Al (t=4.5 mm) specimen, -0.8° spring-go was measured in the test performed with a 140° bending angle in a 20 mm wide mold width. When the bending angle was 150°, -1.2° spring-go was measured, and when it was 160°, -0.7° spring-go was measured (Figure 8-b).
The view of the Al+C+Al sample, where the component thickness is 1.5 mm after the test, is given in Figure 9. After the experiment, delamination occurred between the aluminum and fiber layers. It can be said that the reason for the delamination is that the stresses formed between the aluminum and carbon fiber sheets during the bending process are more significant than the adhesive bond strength [34]. Similar damage behavior has also been observed in studies in the literature [21, 35, 36, 37].
The increase in the mold width from 16 mm to 20 mm caused a rise in the springback and spring-go values. Since the increase in the mold width caused a decrease in the amount of plastic deformation in the total deformation, the springback values increased.
When all samples were examined, it was observed that no tear or crack occurred in the aluminum plate after bending. It has been observed that there are delaminations between the aluminum and fiber layers only due to the deformation effect. If smaller bending angles were used, cracks and damage might have occurred on the surfaces of the samples. However, since the bending levels applied were low, no damage happened to the aluminum in this study.

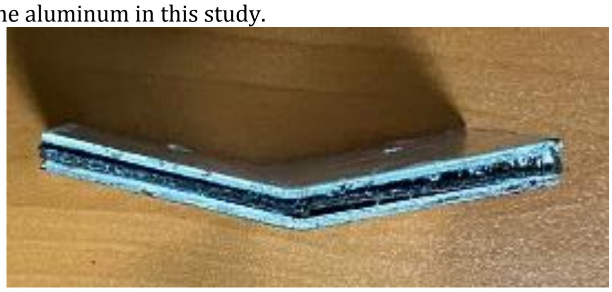
Figure 9. Al+C+Al (t=4.5 mm) for 20 mm mold width at 150° bending angle

4 Conclusion

Fiber metal laminates (FMLs) are a hybrid sandwich composite material of metal sheets and fiber-reinforced composite layers. Fiber-reinforced composites have been increasingly used in many fields, such as aircraft, aerospace, automobile, ship, and wind turbine blades. The use of FMLs is increasing, especially in the production of aircraft fuselages. However, the springback behavior that occurs during the creation of FML parts negatively affects the form of the final product. In the present study, the springback and spring-go behavior of FML composites were investigated by performing a v-shaped brake-forming process. FML composites of different thicknesses were bent at 140°, 150°, and 160° bending angles with 16 and 20-mm mold widths. The results obtained from the experiments are listed below;

- It has been observed that the springback angle decreases with increasing specimen thickness at the same bending angle.
- It was noted that when the bending angle increases, the springback angle decreases.
- Selection of the correct V-shaped die is essential before starting experimental studies. It has been observed that when the correct V-bending die is used, results closer to the desired angle value are obtained.
- It has been observed that mold width also affects springback. As the mold width increased, springback values also increased. The increase in the mold width caused a decrease in the amount of plastic deformation in the total deformation, and the springback values increased. It is estimated that if a lower mold width is used in future studies for these composite materials, the springback values will decrease.
- As the bending angle increased from 140 to 160, the springback in the Al+CG+Al (t=3 mm) specimen decreased from 2.2 to 0.8, decreasing by 64%.
- The type of reinforcement fiber also has a significant impact on springback or spring-go.
- The lowest springback value was obtained in the Al-CG-Al (t=4.5 mm) specimen with a springback value of 0.4° at a bending angle of 160° and a mold width of 16 mm.
- The highest springback value was obtained in the Al-C-Al (t=4.5 mm) specimen with a springback value of 15.1° at a bending angle of 140° and a mold width of 20 mm.
- The lowest spring-go was obtained as -0.3° at 160 die angle, and 16 mm die width in the Al-G-Al (t=4.5 mm) specimen.
- The highest spring-go was obtained as -1.7° at 150 die angle and 20 mm die width in the Al-A-Al (t=3 mm) specimen.

5 Author contribution statements

Author 1 has participated in the design of the study, performed the experiments and drafted the manuscript. Author 2 has contributed to the manuscript and provided the initial idea, and to the design and supervision of the study. All authors have read and approved the final manuscript.

6 Ethics committee approval and conflict of interest statement

There is no need to obtain permission from the ethics committee for the article prepared.
There is no conflict of interest with any person/institution in the article prepared.

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