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State-of-the-art Review of Springback Behavior of Polymers

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ABSTRACT

The spring-in and spring-back behavior of polymers is intricate and influenced by various process parameters and mechanisms, including interply slip, anisotropic thermal expansion, and crystallization, all of which can lead to residual stresses. Composite materials made of metal and polymer are being investigated by researchers as a promising alternative to monometallic materials due to their superior properties. However, the number of studies related to metal/polymer/metal laminates on the same topics is relatively limited. A comprehensive review study was carried out with a focus on research works that were conducted with the consideration of different process parameters, such as radius of die and punch, friction, and force applied by blank holder, in order to observe their impact on the springback behavior of polymers. Springback on polymer components depends on the accuracy of appropriate materials and the consideration of appropriate experimental strategies. However, due to their viscoelastic properties, polymers demonstrate distinctive springback behavior. Furthermore, when subjected to deformation, polymers experience a combination of elastic and viscous responses, resulting in immediate elastic recovery and time-dependent viscoelastic relaxation. This intricate behavior presents difficulties in precisely forecasting and managing springback. To enhance the control and optimization of springback in polymer-based manufacturing processes, it is essential to improve the understanding of polymer behavior under diverse loading conditions and to refine simulation techniques accordingly. This review focuses on springback prediction models specific to polymers.

1. Introduction

Metal-polymer laminates, composed of a polymer interlayer sandwiched between two metallic cover sheets, exhibit several advantages over homogeneous metal sheets. First, they possess a significantly lower density [1] and superior sound and vibration damping characteristics [2]. As a result, they are suitable for use as replacements for current materials in various automotive components, such as fenders, doors, and certain interior panels. Secondly, the lower yield strength

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of metal-polymer laminates compared to solid metal sheets requires less force during the forming process. This results in reduced tool wear, lighter press loads, and cheaper dies [3]. Thirdly, metal-polymer laminates offer an excellent surface finish and demonstrate bending rigidity that is nearly equivalent to that of a simple metal sheet of the same total thickness. Consequently, they can provide similar bending stiffness to homogeneous metal sheets but with lower weight. Furthermore, metal-polymer composites offer several advantages over solid materials in engineering applications, including a high strength to weight ratio, excellent thermal and electrical insulation, and superior acoustics and damping properties, as noted in [4–7]. Typically, metal-polymer-metal sandwich panels are constructed using thermoplastic polymers, like polyethylene or polypropylene, as cores, with outer skins made of steel or aluminum sheets [8]. Carradò and Ravindra [9] provided a broad overview of metal/polymer/metal sandwich systems and delved into an in-depth discussion about their varied applications. Kirubakaran et al. [10] concentrated on the mechanical and vibration attributes of fiber metal laminates (FML) engineered with multi-order energy-absorbing flax fiber and high-strength basalt fiber stacking, encased within titanium sheets. Fiber metal laminates, such as GLARE, ARALL, and CARALL, are known for their high strength to weight ratio and are used in aerospace applications for bulkhead and cargo floor structures, leading edges, tails, and upper fuselage skins of aircrafts such as the A380, as stated in [11–13]. In automotive applications, composites are preferred for their weight reduction and dent resistance, and aluminum-polymer sandwich panels, called BONDAL, are commonly used, while steel-polymer panels, called HYLITE, are used for damping, as indicated in [14, 15]. Due to their lightweight nature, portability, and ease of fabrication, sandwich panels are increasingly utilized in the construction of temporary houses [16], and are also useful for facades, space partitioning, and environmental enclosures [17].

Springback refers to elastic recovery that occurs in sheet metal parts after the forming force is withdrawn, leading to a deviation from the die shape. This phenomenon is quantified by measuring changes in angles or other dimensional variations. A phenomenon known as "springback" occurs when metal is bent or formed and then returns to its original shape [18–20]. The outer layers of a metal are stretched while the inner layers are compressed when the metal is bent or otherwise formed. The metal springs back when the force is released because the outer layers try to take on their original shape. Further, springback is characterized by minor deformations that are comparable in size to other elastic deformations in metals. This had led researchers to the belief that it was a straightforward process compared to the significant deformations required for metal forming. However, there has been a significant increase in understanding of two important aspects of springback. Firstly, the plastic response of the metal/polymer during large-strain deformation needs to be accurately predicted [21–25], which requires high precision because it directly affects the stress distribution within the material before external forces are removed. Secondly, even though unloading is typically linearly elastic in most cases, it can exhibit notable deviations from ideal linear behavior. Springback is a common flaw in polymer composite structures that has piqued the interest of researchers [26–31]. Hence, it has been of interest to study the elasticity a metal has once it reaches a point of deformation. Moreover, in the case of metal forming, springback is a geometric error that results from elastic recovery and can be challenging to reduce or completely eliminate. The ultimate shape of a part's springback, which occurs due to the cumulative impact of its entire forming process, is significantly influenced by various factors, including die geometry, material properties, and the amount of frictional contact involved in the sheet metal forming process.

Sandwich laminates consisting of metal and polymer layers separated by a core thickness possess an elevated flexural stiffness to weight ratio [32–35]. Moreover, the core acts as a separator between the skins. Notably, certain laminates, such as those made of aluminum/polypropylene/aluminum

[36–39] or steel/polypropylene/steel, have been utilized in body panels like hoods, trunks, and dashboards. The improved stiffness to weight ratio of these laminates has led to substantial reductions in weight. Numerical and experimental studies were carried out by Parsa et al. [40] to examine the V-die bending of sandwich laminates made of Al3105/polypropylene/Al3105. The researchers discovered that intact components exhibited a springback angle that fell between the springback angles of the individual layers. Li and Wang [41] developed an analytical model that utilized Euler-Bernoulli beams subjected to interfacial shear stresses in the bending arm. This model aimed to predict the springback and side-wall curl of progressive microcracking laminates (PMLs) [42–46]. Various methods were employed to investigate springback behavior of laminated sheets in different bending processes [47–51]. Pure bending was used in analytical studies utilizing primary and advanced bending theories [52–59]. Additionally, experimental and numerical investigations were carried out on springback in double curvature bending [60–70]. The shear cutting process was also studied to understand the behavior of metal/polymer/metal laminated sheets and determine the force required to prevent failure [71]. In the V-bending process, a numerical and experimental study was conducted on metal/thin viscoelastic polymer/metal sandwich sheets in [72]. Numerical and experimental techniques were employed to investigate V-die bending and the phenomenon of springback in [73]. Richter et al. [74] conducted an analysis of the deep drawing process of St/PP-PE/St laminates using both finite element analysis (FEA) simulations and experimental investigations. They elucidated the influence of different parameters on the deep drawing process. Link [75] manufactured three laminates consisting of steel skins and polypropylene cores, which led to a reduction in overall density ranging from 35% to 46% when compared to solid steel.

Fiber metal laminates are notably superior to those of their constituent elements, exhibiting exceedingly high strength-to-weight ratios. Thermoforming poses challenges when it comes to fiber metal laminates (FMLs) and progressive microcracking laminates (PMLs). Mosse et al. [76] explained that the polymer must be heated adequately to facilitate composite flow during forming, but also that it needs to cool down to a dimensionally stable state after forming to facilitate part removal from the die. The arrangement of fibers in relation to the successive layers of the laminate determines whether the resulting composite is anisotropic or isotropic [77, 78]. This process can lead to wrinkling, which is exacerbated by the inadequate resistance of the viscous polymer to suppress buckling phenomena, in steel/carbon-fiber-reinforced polyamide 6/steel laminates as observed by Tekkaya et al. [79] and in AA1200/glass-fiber-reinforced polypropylene/AA1200 sandwich laminates as indicated by Rajabi et al. [80]. Increasing the blankholder forces can mitigate wrinkling, similar to monolithic sheet metal forming. Mosse et al. [81] discovered that shape errors, akin to springback, can be reduced by increasing the feed rate during channel-forming of Al5005/glass-fiber-reinforced polypropylene/Al5005 laminates because higher feed rates keep the laminate within a narrower temperature range. Bilayer material bending springback analysis was examined by Nikhare [82] for the two different materials they have used in their study; aluminum and composite. At a temperature of 140 °C, Kim et al. [83] created a sandwich sheet called AAPPAA (Alternating Aluminium-Polypropylene-Aluminium-Polypropylene-Aluminium) by roll bonding a pre-rolled polypropylene core sheet between two skin sheets made of AA5182 aluminum alloy. Choi et al [84] examined the complex behavior of fiber suspensions. As shown in Figure 1, Mrzljak et al. [85] focused on FML made from AA6082 sheets combined with unidirectional glass and carbon fiber-reinforced polyamide 6.

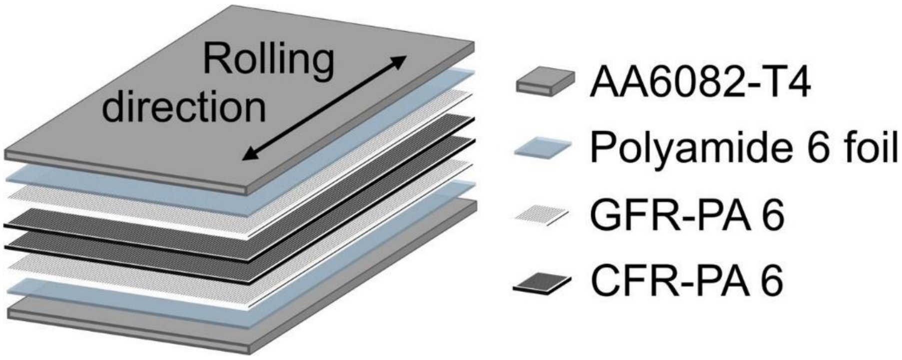
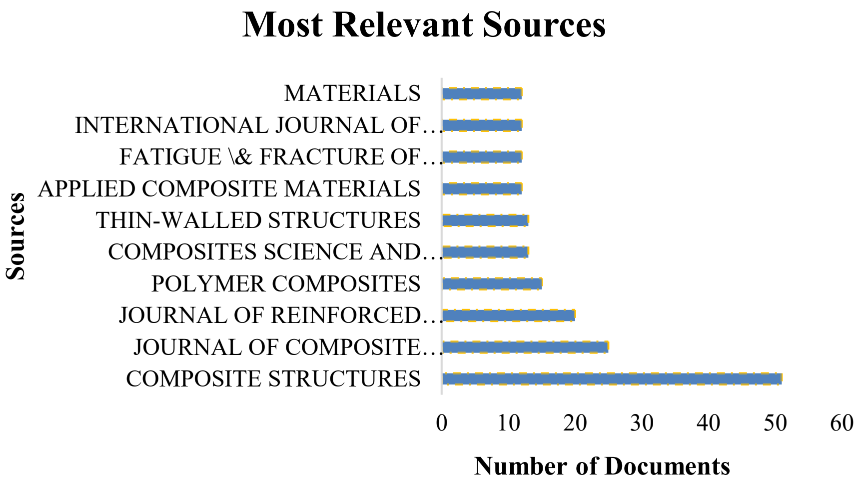
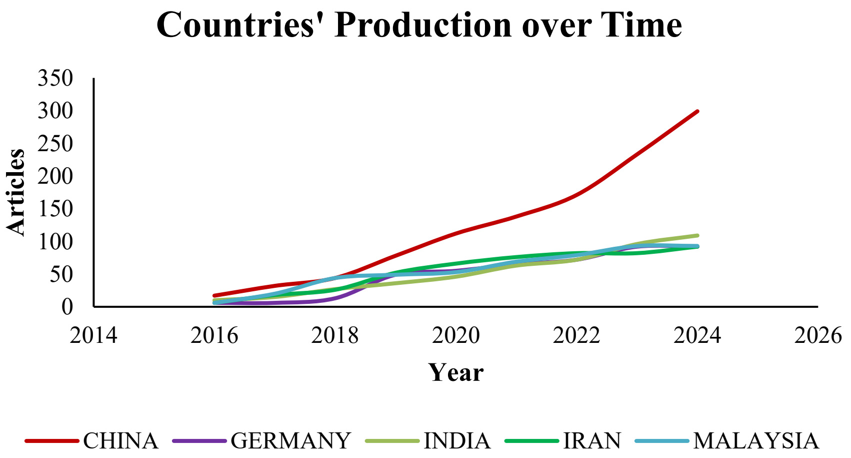


Fig. 1. Diagram illustrating the setup of a thermoplastic-based fiber metal laminate with a 2/1 metal-to-FRP ratio [85]

Springback can be a significant problem in metal-polymer forming processes because it can result in parts that do not meet the desired specifications. To compensate for springback, manufacturers may over-bend or over-form the metal, anticipating that it will spring back to the desired shape. Alternatively, they may use materials that are more resistant to springback, or they may use specialized tooling and techniques to reduce or eliminate springback. Ouled Ahmed Ben Ali and Chatti [86] employed various machine learning techniques such as linear regression, artificial neural network and support vector machine to forecast the springback of the sandwich panel during the three-point bending process. Solfronk et al. [87] examined the impact of computational models and mesh strategies on the prediction of springback in a thin sandwich material comprising micro-alloyed steel. Li et al. [88] researched effect of friction on pipe springback, which revealed that friction has little impact on springback in free bending process. Moreover, numerous studies have explored the springback of sheets using finite element analysis (FEA) simulations [89–93]. Qadeer et al. [94] determined the mechanism that governs the springback in single point incremental forming (SPIF) of laminates and examined the precision. Cheng et al. [95] explored the insertion mechanism of an ultrasound-guided insertion process through numerical simulation, culminating in a final crack resulting from needle extraction and prepreg springback. However, the usage of metal-polymer-metal sandwich laminates is on the rise because of their ability to reduce weight and their high flexural stiffness to weight ratio. In order to meet the requirements for safety and the environment, extensive research has been done in recent years on the development of lightweight materials that combine metals and polymers, known as composite sandwich metal/polymer materials. However, the geometry of the final product can be significantly impacted by springback, which is a crucial factor. If not adequately managed, it can lead to a negative impact on product's quality and precision. Furthermore, the magnitude of springback is influenced by numerous factors, such as mechanical properties of the material [96–101], tool geometry [102–104], stress distribution and levels, deformation, and processing parameters like lubrication and clamp pressure, among others. The Bibliometrix R package furnishes a toolkit for quantitative analysis in scientific metrology, designed within the open-source environment and ecosystem of R, which was used to analyze data from web of science. Publications selected from web of science core collection on the presently discussed research area is shown on Figure 2, indicating the most relevant sources and country production over time. Based on area of interest on web of science in different sources, the number of research studies published in the field of springback using polymer core is on the rise.



a)



b)

Fig. 2. (a) Web of science core collection on most relevant sources published from 2022 to 2024; (b) Documents by territory; country production over time

2. Springback and sidewall curl measurement

The quantity of elastic recovery that occurs can be influenced by yield strength (Y) and modulus of elasticity (E) of the material. Gardiner [105] has derived an equation to approximate the amount of springback.

$$\frac{R_i}{R_f} = 4\left(\frac{R_i Y}{ET}\right)^3 - 3\left(\frac{R_i Y}{ET}\right) + 1 \tag{1}$$

The model considers material thickness (*T*), initial (*R$_i$*), and final (*R$_f$*) bend radii, and enables the prediction of the final bend angle (*R$_f$*) given the values of (*R$_i$*), (*Y*), and (*E*). The assumptions underlying the development of the model are:

- A fiber's strain increases with distance from the neutral axis
- Plane stress condition
- Midway through the sheet thickness, the neutral axis is located
- Elastic-perfect plastic material behavior

When it comes to bending single layer sheet metal, the degree of springback can be quantified by the springback factor (*K$_s$*), which is depicted in Figure 3. The formula for (*K$_s$*) is:

$$K_s = \frac{\alpha_f}{\alpha_i} = \frac{(2R_i/T)+1}{(2R_f/T)+1} \tag{2}$$

The springback factor (K_s) is calculated using initial (α_i) and final (α_f) bend angles. A value of K_s=1 implies that there is no springback, while K_s=0 indicates complete elastic recovery.

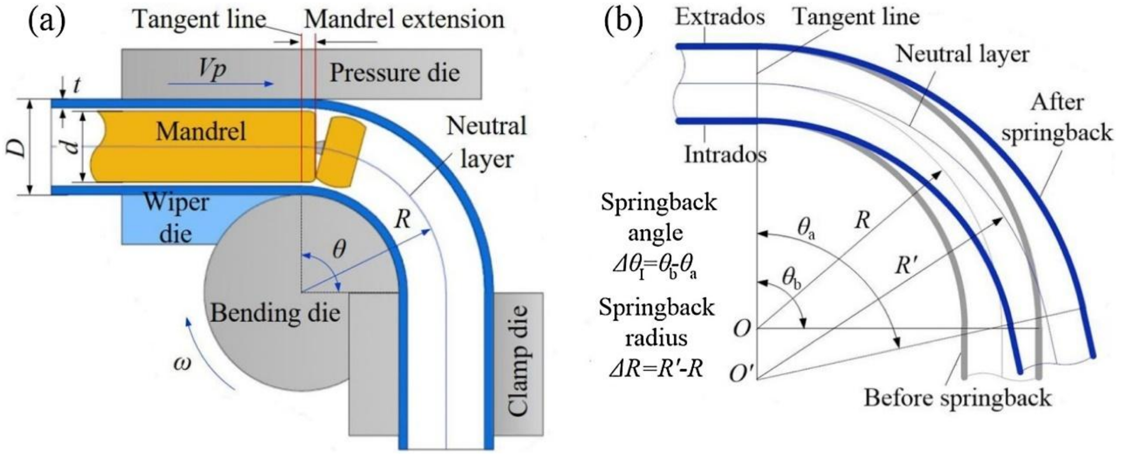


Fig. 3. Illustrations of rotary draw tube bending: (a) Bending procedure (b) Springback during unloading [106]

2.1 Springback

Springback refers to the departure from the desired shape of a formed component, resulting from the elastic rebound that occurs once the forming force is eliminated. It is measured as a change in angle or other dimensional deviations. Figure 4 illustrates the elastic strain recovery causing springback in a specimen loaded beyond the yield strength and unloaded. This deviation from desired dimensions can create problems in assembly and subsequent forming operations like trimming or flanging.

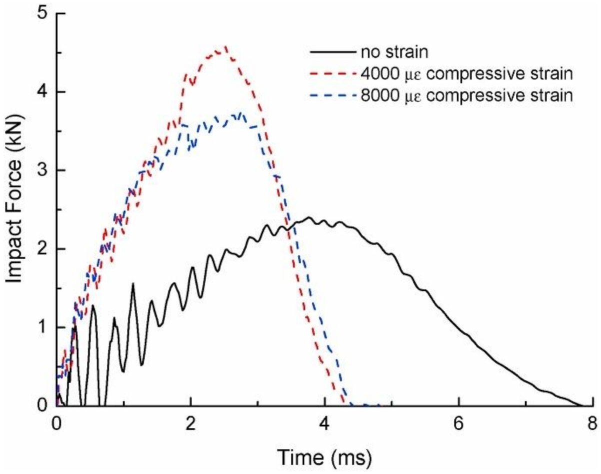


Fig. 4. Force-time impact curves for Fiber Metal Laminates (FML) under unloaded and preloaded conditions [107]

2.2 Springback bending

Bending refers to the process of applying a force to a metal sheet or plate, causing it to bend and acquire a curved shape as depicted in Figure 5. As a result of bending, the metal/polymer experiences both elastic and plastic deformations, with the elastic deformation causing the material to return to its original shape after the bending force is eliminated. Hahn et al. [108] conducted a study to examine how the thickness of the face sheet in fiber-metal laminate (FML) samples affected springback. The findings showed that the springback tendency in FML specimens increased across all bending angles as the thickness of the face sheet was augmented. This rebound effect is commonly referred to as bending springback, which is frequently observed in metal forming processes. The typical level of springback is proportional to the quantity of elastic deformation that is regained upon removal of the bending punch. This aligns with the residual stress condition that is established after bending, which occurs during unloading as demonstrated in a diagrammatic form, expressing the springback as a springback ratio [109]. Gao et al. [110] examined the extensive deformation bending characteristics of a single-ply fabric reinforced polymer composite (SpFRPC) using the innovative counterweight balanced column bending test (CWB-CBT) alongside microscopic analysis. Naik et al. [111] conducted FEA on V-bending of manufactured sandwich panels in order to examine two specific aspects: weld failure at the skin-core interface and the occurrence of springback in the sandwich panel.

$$K_s = \frac{\theta_f}{\theta_i} \tag{3}$$

Alternatively, the springback can be described by its variation $\Delta\theta = \theta_i - \theta_f$ or percentage change.

$$\Delta\theta\% = 100 \times \frac{\theta_i - \theta_f}{\theta_i} \tag{4}$$

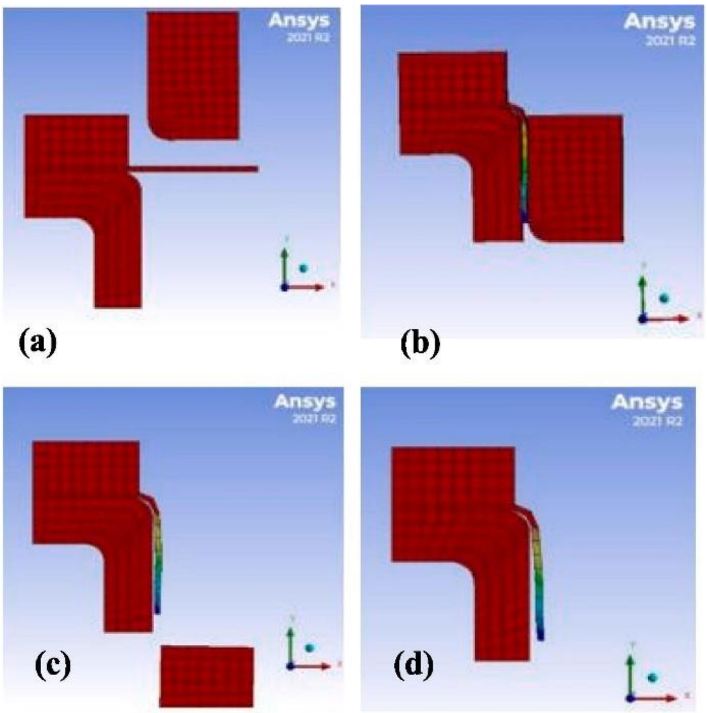


Fig. 5. (a) L-Bending setup, (b) L-Bending, (c) After L-bending, (d) Spring back of the sheet [112]

2.3 Mechanical properties

To explore the mechanical characteristics, the rule of mixture [113] stands as a suitable approach for computing specific parameters such as strength and Young's modulus, as illustrated for each combination below:

$$T_{\text{Sandwich}} = f \times P_{\text{Core}} + (1-f) \times P_{\text{Skin}} \quad \text{where} \quad f = \frac{T_{\text{Core}}}{T_{\text{Sandwich}}} \tag{5}$$

The core sheet's volume fraction is denoted as f, with a thickness of T_{Sandwich}, and the property to be computed (such as density, YS, UTS, or elastic modulus) is represented by P_{Skin}. For instance, the tensile strength of the sandwich materials (SMs) can be determined by employing the values for the individual materials and their proportions in the sandwich. The estimated and measured values were then compared using the Rule of Mixture (RoM). Permanent deformation occurs when the changes in a material's structure exceed its maximum elastic limit. Nonetheless, this deformation is not necessarily the final state since, after the removal of the applied forming pressure, the material tends to revert to its original location. Figure 6 (a) illustrates the geometries of a 1.5 mm thick sandwich sheet deformed into a double curvature with a tool set and a post-unloading process and Figure 6 (b) shows the illustration of specimen before and after springback. Futhermore, comparison of FEA and experimental results on springback prediction are provided in Table 1.

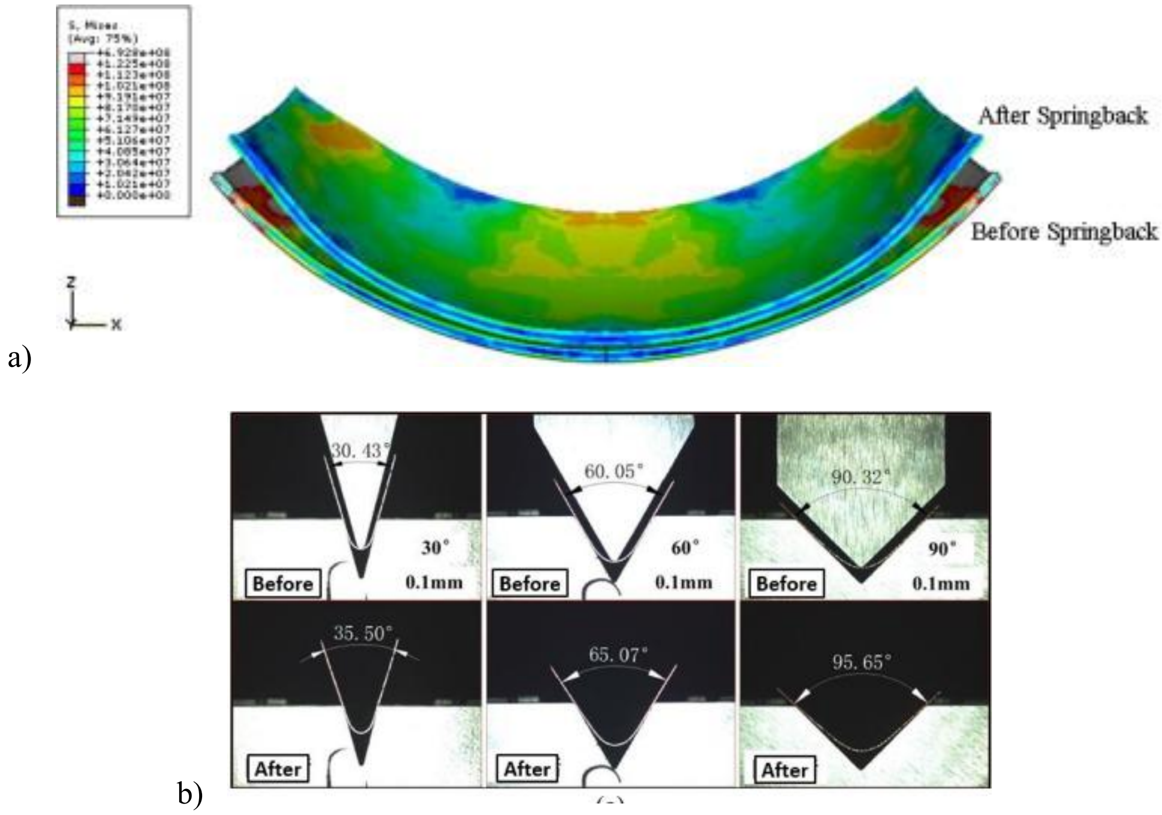


Fig. 6. (a) Double curvature bending, both before and after unloading [114]; (b) Specimens before and after springback [115]

Table 1
Comparing the springback prediction from FE simulation with the results of experiments [116]

	Punch radius (mm)	Springback coefficient		Relative error (%)
		FEM prediction	Experimental	
1	10	0.9819	0.9635	1.91
2	15	0.9104	0.9149	0.50
3	20	0.9019	0.8976	0.49
4	25	0.8743	0.8800	0.65
5	30	0.8489	0.8670	2.08
6	35	0.8273	0.8442	2.01
7	40	0.8084	0.8181	1.20

3. Effect of stamping velocity on the occurrence of springback

Effect of stamping speed on springback can be categorized into three factors. Firstly, as the stamping speed increases, dislocation density in the sheet also increases, resulting in significant work hardening and ultimately leading to greater springback. Secondly, some of the energy converted during the stamping process is transformed into heat, causing the temperature of the sheet to rise. As the temperature increases, the yield stress and resistance to deformation of the sheet decrease, resulting in reduced springback. Moreover, higher stamping speeds can result in incomplete deformation of the formed parts, causing the elastic deformation to exceed the plastic deformation. Consequently, this leads to an overall increase in springback. Moreover, stamping velocity, also known as forming velocity, refers to the speed at which the punch and die come into contact during the metal stamping process. Figure 7 depicts the impact of stamping speed on springback. This is a common phenomenon that occurs after forming a metal sheet or part and refers to the elastic recovery of the material after it has been deformed. It should be noted that the stamp forming of polymers [117–124] have been investigated in a substantial amount of recent research works. Researches show that stamping velocity can indeed have an effect on the occurrence of springback, higher stamping velocities tend to result in increased springback, while lower velocities can help minimize springback [125]. The relationship between stamping velocity and springback is primarily influenced by the material properties and the process parameters [126]. Furthermore, when the stamping velocity is high, the deformation of the metal occurs rapidly, causing the material to undergo higher strain rates, leading to rapid deformation and increases elastic recovery during springback. Hence, the higher the strain rate, the more likely the material is to exhibit elastic behavior and spring back to its original shape.

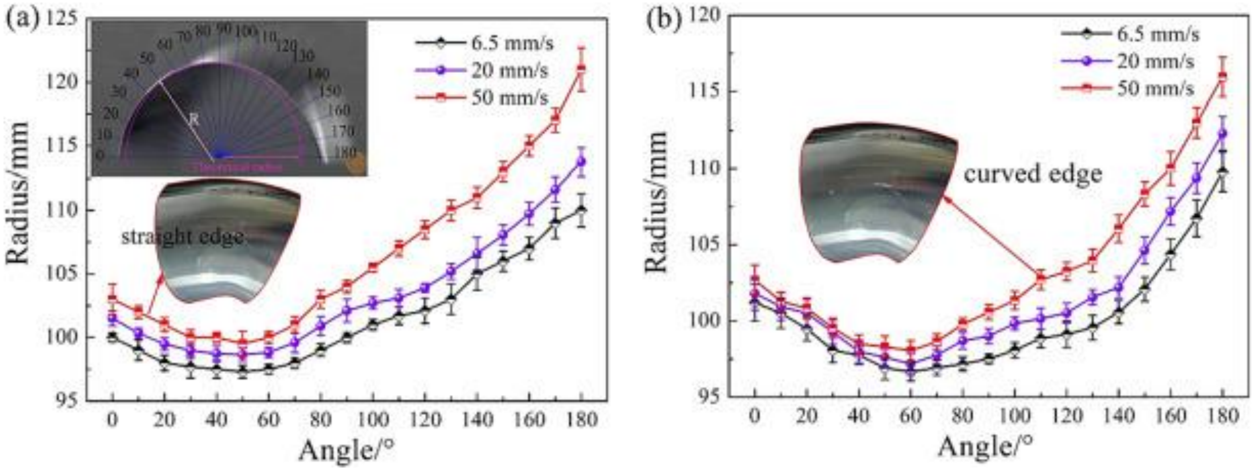
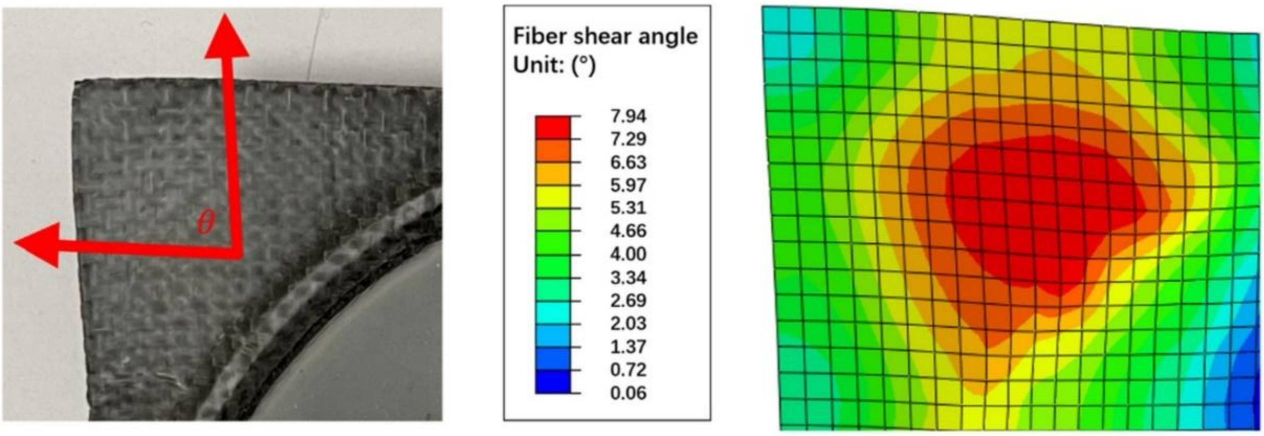


Fig. 7. Impact of stamping speed on springback: (A) straight edge and (B) curved edge [127]

3.1 Springback angle

The springback angle is calculated by subtracting the forming angle after springback from the forming angle prior to springback. To determine the forming angle, one can measure the angle between the edges of the straight sections of the inner flange of the tube. Figure 8 shows the comparisons between different fiber angles. According to experiments conducted by Zhu et al. [128], the springback angles measured when using core fillers were lower than those measured when using PVC fillers, even though the peak equivalent stress values were higher with core fillers. In addition to that, they have also found that the springback angle decreased as the number of cores were increased and the PVC mandrel underwent plastic hardening. However, with an increase in step size, Jain et al. [20] noticed that springback was also observed to be increasing. Özdemir et al. [129] studied how molding force and springback in the deep drawing process of thermoplastic composite laminates were impacted by different forming parameters.



$\theta \approx 83°$

$\theta \approx 82°$

Fig. 8. Comparison of fiber angles [124]

3.2 Effect of punch radius on springback

Springback measurements usually begin by determining the angle difference between the bent and unbent portions. This value is then divided by the tooling angle to obtain the final result. If the quotient is equal to one, denoted by K_s, then no springback occurs. Every material, including polymers, possess some degree of elasticity. When subjected to plastic bending, they undergo an elastic recovery after the load is removed. Experiments conducted by Chan et al. [130] show that the valley spring-back angle decreases as the punch radius increases. Figure 9 shows the springback versus punch radius. Harhash et al. [131] examined the forming characteristics of steel/polymer/steel (SPS) sandwich composites across different bending angles (60, 90, and 150°) and punch radii (1.5, 3, 6, and 12 mm). Table 2 depicts the effect of punch radius and thickness.

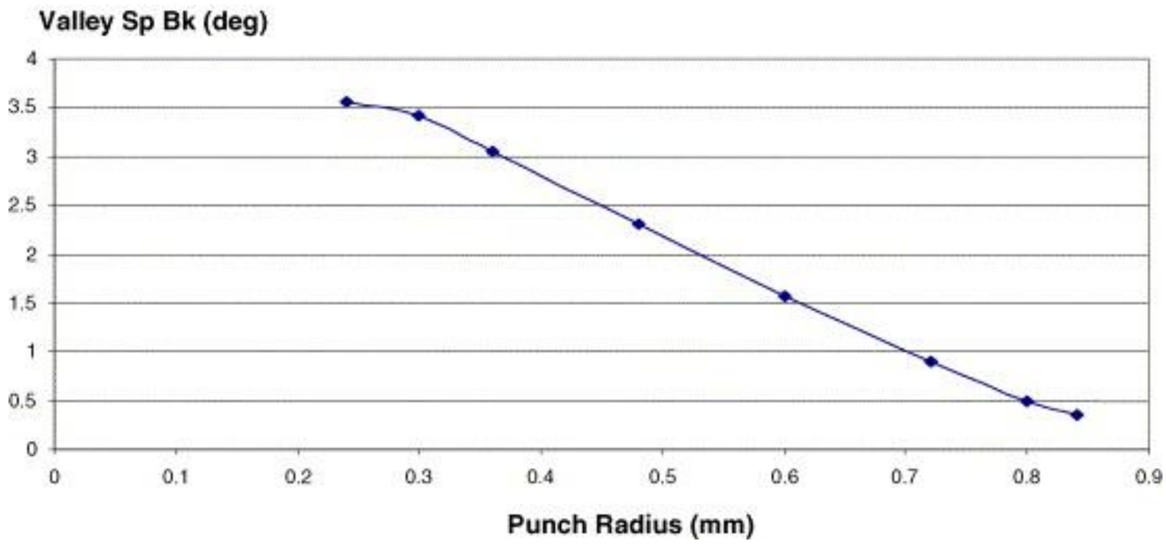


Fig. 9. Valley spring-back versus punch radius [130]

Table 2
Effect of punch radius [132]

S/N	Punch radius (mm)	Sheet thickness (mm)	Spring back (^{0})
1	2	0.5	0^0 58'
2	2	1	41
3	4	0.5	10 59'
4	4	1	10 4'
5	6	0.5	50 59'
6	6	1	2^0 19

In aerospace industry, fiber-metal laminates (FMLs) like GLARE (glass-reinforced aluminium laminates), ARALL (aramid-reinforced aluminium laminates), and CARALL (carbon-reinforced aluminium laminates) have been developed to address two key objectives; reducing the overall weight of aerospace structural components and enhancing their impact and fatigue resistance. These FMLs have been specifically designed and implemented in the aerospace sector to achieve these goals [133]. In recent years, there has been growing attention towards exploring alternative materials for FMLs. Specifically, there is a notable interest in utilizing magnesium alloy and titanium alloy as constituents in FMLs. This interest stems from the rising need for parts with high strength-to-density ratios. As a result, FMLs incorporating magnesium alloy [134, 135] and titanium alloy have gained increasing attractiveness due to their promising properties. The fabrication of these material systems involves the bonding of composite laminate layers to metal layers [135]. Although the concept is commonly employed in combining aluminum with aramid and glass fibers, it can also be extended to include other types of materials [136]. A classification of FMLs based on the arrangement of metal layers is provided in Figure 10.

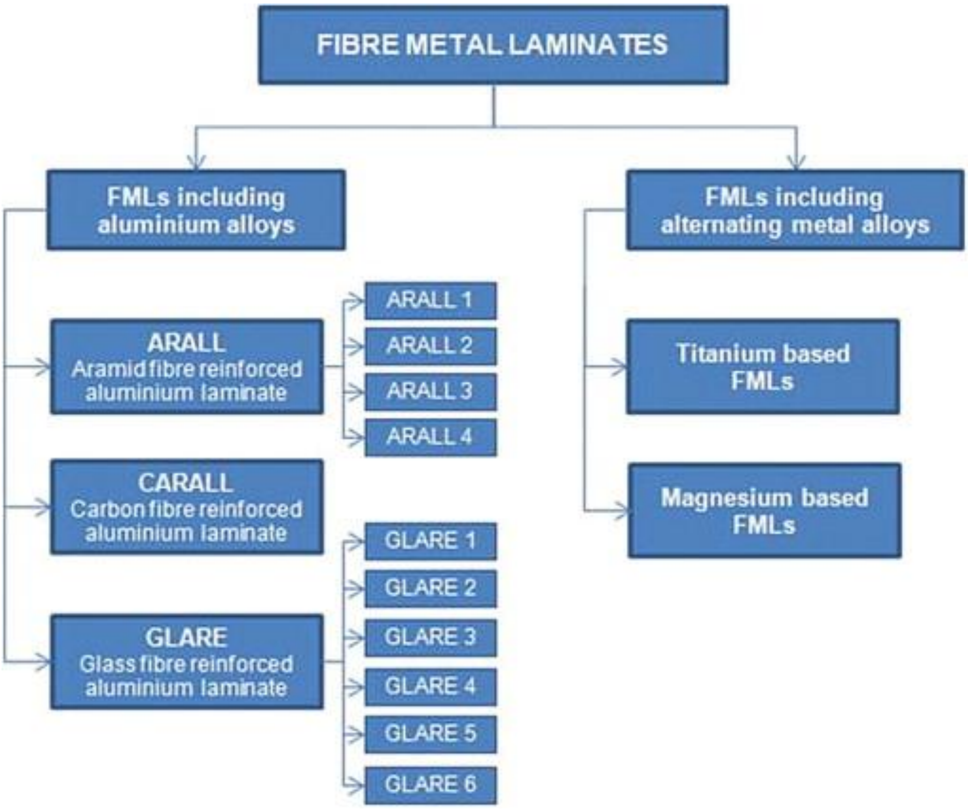


Fig. 10. Classification of FMLs based on metal plies [133]

3.3 Effect of sheet thickness on fiber-metal laminates

FMLs are composite materials made up of conventional fiber reinforced plastics. These materials are enhanced by the inclusion of a metal component, which is usually in the form of foil or mesh layers [137]. The metal component provides the benefit of introducing metallic characteristics to the composite structure [138, 139]. Metal/polymer laminate forming processes often encounter the issue of springback, which refers to the tendency of the metal/polymer laminate material to revert to its original shape after being bent or formed [140]. Extensive research has been carried out to investigate the impact properties of aluminum-based FMLs [141–144]. The degree of springback is influenced by several factors such as material characteristics [145–149], forming process variables [150, 151], and the geometry of the resulting component [152, 153]. Moreover, in the context of laminated sheets, the thickness arrangement of the layers is a significant factor that can impact the extent of springback in sheet metal forming. However, Kella [100] discovered that as sheet thickness increases, the radius of curvature controlling sidewall curl increases as well. Azhdar et al. [154] correlated the springback gradient in the material of the die with the characteristics of the process and the design of the machine equipment. Bikakisf [155] performed research on the springback phenomenon in Glare when it is subjected to brake forming. Based on his findings, he deduced that the tool design and various process parameters, including the punch speed, punch radius, and forming temperature, can significantly influence the degree of springback [156]. In addition, Kazemi et al. [157] demonstrated that the sandwich composites made of AA5754/polyethylene/AA5754 are fitting for replacing aluminum sheets. Table 3 depicts various sheet thinkness effect on springback.

Table 3
Springback values with punch radius and die [100]

Sheet Thickness (mm)	Die and punch radius = 8 mm		
	θ_1 (°)	θ_2 (°)	ρ(mm)
0.8	102.097	84.495	246.543
1	101.676	84.71	259.64
1.2	98.888	85.269	290.165

Regarding the Al/PP/Al laminated sheet, the thickness configuration denotes the proportionate thickness of the aluminum layers and the polypropylene (PP) layer [158]. Figure 11 shows the hot press machine process on springback. Typically, the aluminum layers are thicker than the PP layer to provide structural support and stability to the laminate. The bending behavior and resulting springback of laminated sheet can be influenced by the thickness ratio of layers [140].

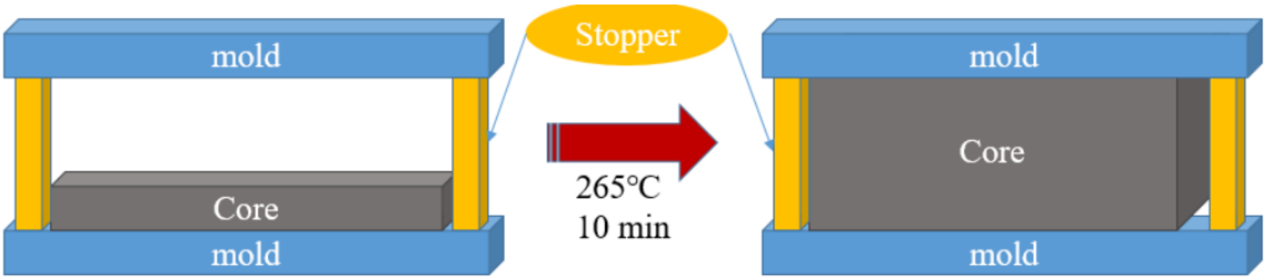


Fig. 11. The process of springback for a PP core using a hot press machine [159]

According to the study carried out by Parsa et al. [114], the springback magnitude rises with an increase in friction coefficient and core thickness, while it declines with a decrease in the bending radii during the double curve bending process. Ouled and Chatti [160] proposed a semi-analytical approach to predict springback in the bending process of thick sandwich panels. Their method involved using calibrated mechanical parameters obtained from experimental load-displacement data. The authors observed a satisfactory agreement between the predicted and experimental springback results. On the other hand, response surface methodology (RSM) is becoming increasingly popular for engineering design applications in industrial settings. Lepadatu et al. [161] employed RSM to optimize springback during the bending process of metallic sheets, considering input parameters such as the die corner radius and punch-die clearance. Additionally, the springback ratios for sandwich are listed in Table 4.

Table 4
The springback ratios for sandwich [159]

Dimension (mm)	SB100%	SB150%	SB200%	SB250%	SB300%
Span length	40	40	70	84	96
Width	35	35	35	35	35
Thickness	2.7	3.3	4.2	4.8	5.7
Length	55	55	80	95	115

Also, the thickness configuration of Al/PP/Al laminated sheet can influence the springback behavior during sheet metal forming [162]. Augmenting the thickness of the aluminum layers in the laminated sheet can reduce springback by improving the structural support and stability of the laminate. The optimal thickness configuration would depend on the specific requirements and constraints of the forming process and the formed part. In a study conducted by Parsa et al. [40], the impact of punch radius and foam thickness on springback in sandwich panels made of aluminum/polypropylene/aluminum was investigated. Table 5 shows springback in a laminated sheet with polymer core. Further, it was observed that a higher sandwich thickness resulted in a reduction in springback. In addition, Figure 12 shows thickness distribution at various stamping speeds.

Table 5
Springback in a laminated sheet made of Al/PP/Al [163].

	Configuration	a	b	C	d	e
AL	t_l (mm)	1		2		0.5
PP	t_2(mm)	1	1		2	1
AL	t_3(mm)		1			0.5
Normalized springback (anal.)		0.169	0.184	0.0774	0.393	0.0692
Normalized springback(FEM)		0.181	0.196	0.0794	0.423	0.0761

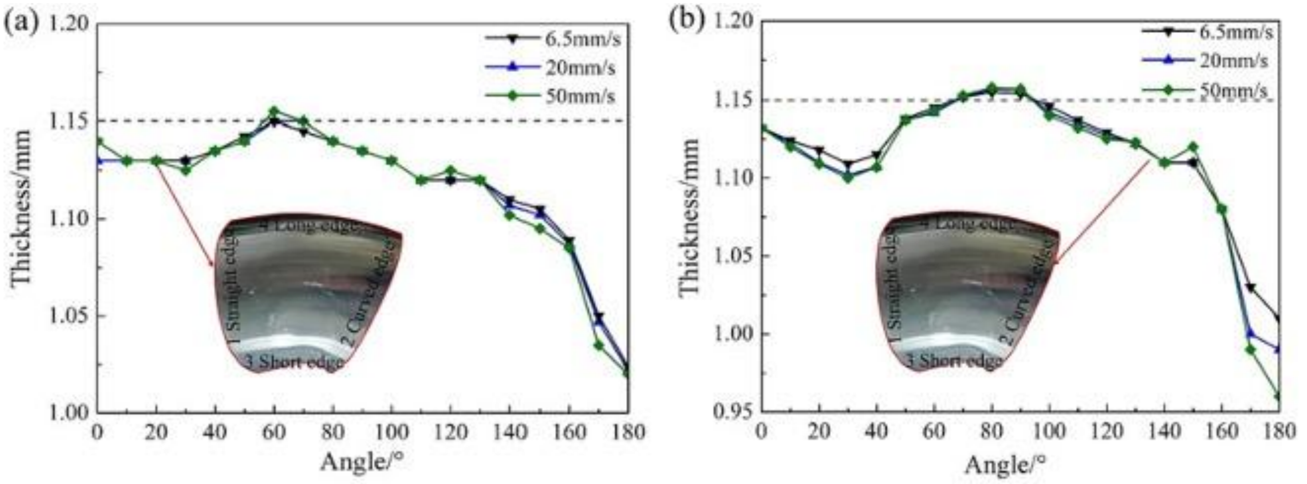


Fig. 12. Thickness distribution at various stamping speeds; (A) straight edge and (B) curved edge [127]

4. Impact of sheet thickness on springback

The stresses at the end of the initial elastic loading exhibit a linear change. An increase in workpiece thickness is expected to result in proportional stress increments. The relaxation of stress, which plays a critical role in determining springback, primarily depends on the initial induced stress. In their study, Seyed Yaghoubi et al. [164] examined how the thickness of fiber metal laminate (FML) and the mass of the impactor influenced the impact response of glass-reinforced fiber metal laminates (GLARE5 FMLs).

4.1 Micrograph investigation on springback

The macro-scale behavior of springback in sheet metals has been studied for many years, with the first analytical model for pure bending developed being by Gardiner [105]. Additionally, various researchers have made improvements to the springback prediction model from different perspectives, including non-uniform deformation, stretch-bending and plane-strain conditions [165–167]. Micrographs are images obtained through microscopy, and they can be used to investigate the microstructure of materials, including those that exhibit springback behavior. Micrographs can help to visualize the deformation and microstructural changes that occur during the forming process and can provide insights into the damage mechanisms in unfilled and filled Glare subjected to tensile loading that influence springback as shown in Figure 13. Xu et al. [55] enhanced the springback model by taking into account the transverse stress in microforming. Hahn et al. [108] stated that when the fibers are aligned at 90 degrees, they cannot withstand the pressure exerted by the punch at forming temperature. For instance, the microstructure of a metal sheet before and after forming can be observed using optical or electron microscopy.

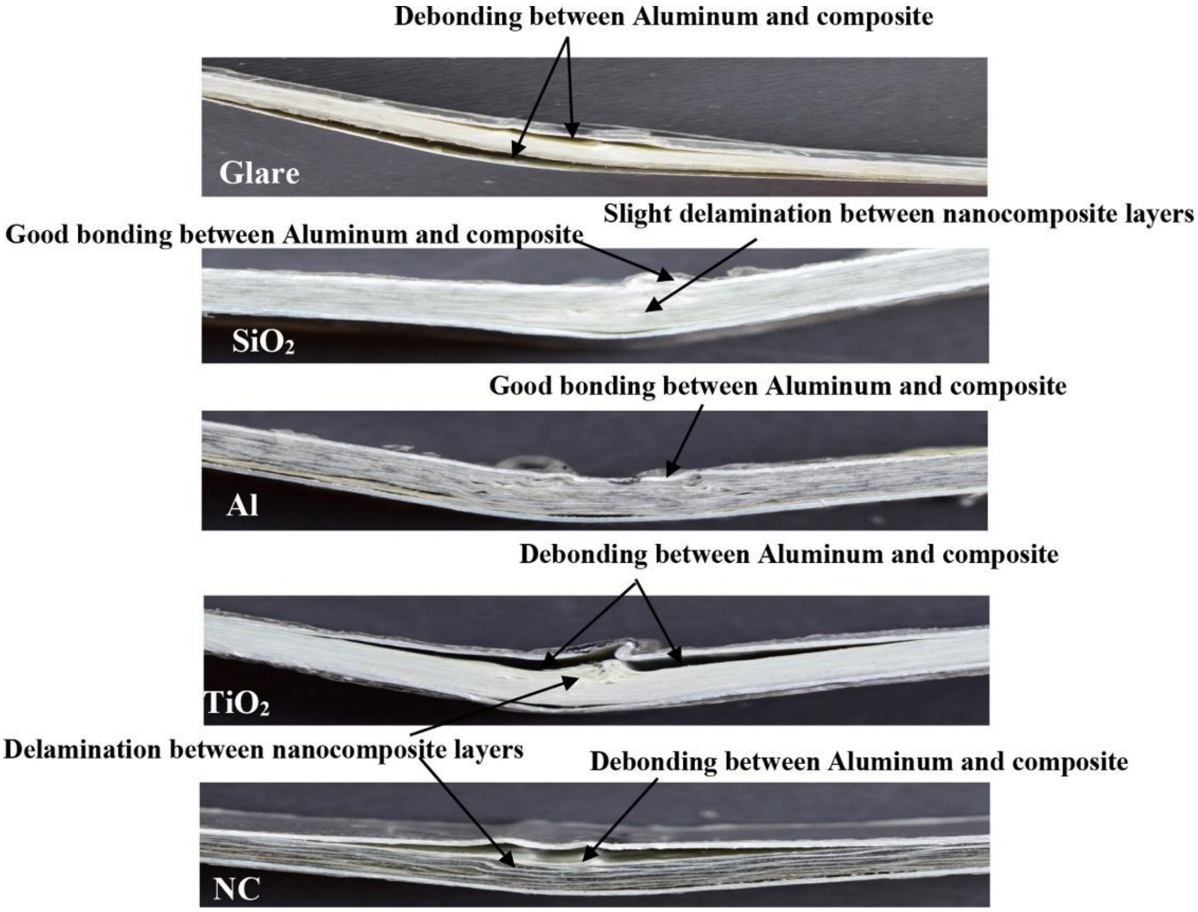
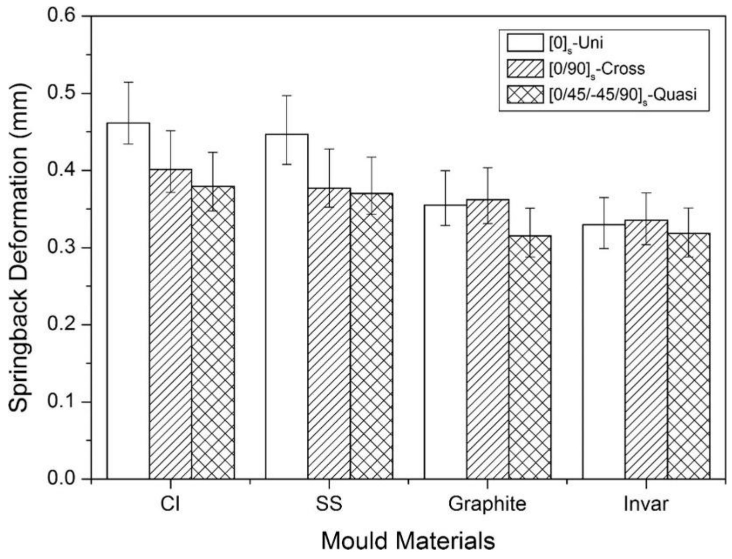


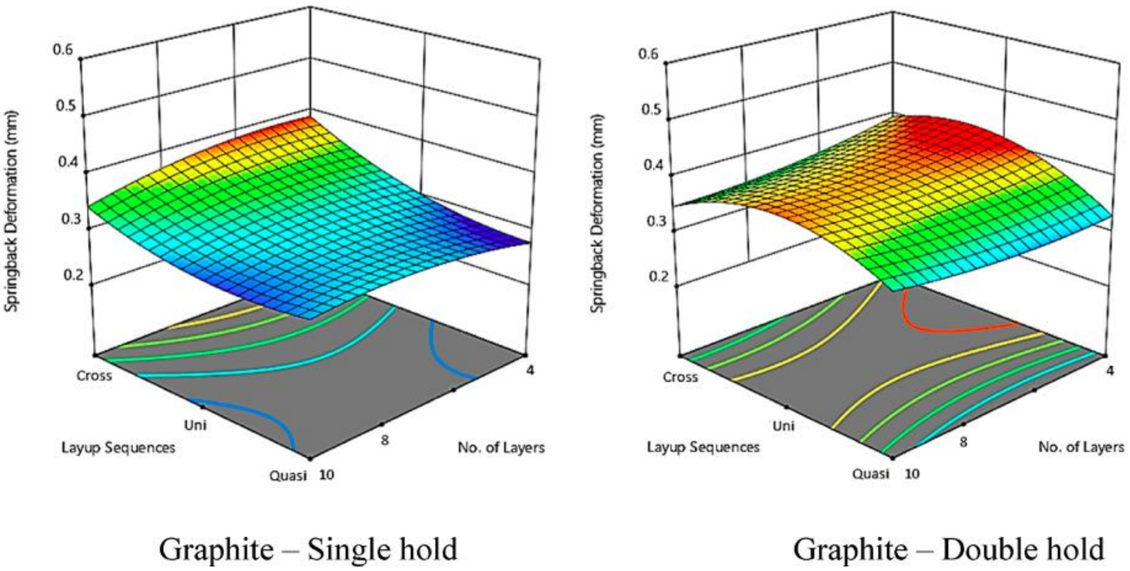
Fig. 13. The damage mechanisms in FMLs under tensile loading [169]

This allows for the identification of any changes that may have occurred due to the forming process, such as changes in grain size, texture, and dislocation density. Additionally, micrographs can also be applied for the examination of the distribution and morphology of inclusions, defects, and other features that may influence springback behavior. Zhou et al. [168] provided an explanation of potential causes for the terminal failure morphology analysis. By examining micrographs of samples with varying springback behavior, researchers identified potential relationships between the microstructure and springback and developed strategies to mitigate or control springback.

The springback deformation of cross-ply laminates exhibits greater magnitude compared to unidirectional laminates when graphite and invar molds are utilized. Figure 14 (a) shows the influence of lay-up sequence on the occurrence of spring-back deformation. This can be attributed to the constrained transverse contraction of the laminate, strains caused by chemical shrinkage, and a predominantly thickness-oriented thermal contraction. These factors collectively contribute to an amplified springback deformation. Figure 14 (b) depicts response surface graphs of spring-back deformation.



a)



b)

Fig. 14. (a) Effect of lay-up sequence on spring-back deformation; (b) Response surface graphs of spring-back deformation (Graphite) [170]

4.2 Methodology for analyzing springback

The methodology for analyzing springback involves a systematic approach encompassing various steps [171–173]. Utilizing numerical simulation software, the forming process is then simulated to predict the springback behavior of the component, encompassing material behavior, tooling, and process conditions. Cheng et al. [174] employed a finite element analysis (FEA) model of multi-pass roll forming (RF) process. Subsequently, the simulation results were validated against experimental data obtained from physical forming trials [175, 176]. Gardiner [177] laid the theoretical groundwork for the analysis of sheet bending and springback during the 1950s. Zhang et al. [178] conducted theoretical calculations to compensate for springback in a doubly curved plate. Numerous investigations into springback compensation and adjustment have been conducted in recent years

[179–187]. Zhang et al. [188] examined springback in the roll forming of microchannels and found that the conventional method for predicting springback is inadequate, as the bending radius is similar to the thickness of the sheet.

4.3 FEA modeling of the press forming process FMLs

Finite element analysis (FEA) was employed to analyze FMLs using a range of elements such as beams, shells, and solids. This analysis was performed using either the commercial software ABAQUS or similar programs [189–196]. Figure 15 shows the residual stresses developed on composite laminates due to springback. Additionally, the references cited provide detailed information regarding the element formulations and numerical procedures utilized in these programs. By carefully adjusting numerical tolerance, mesh size, and integration strategy, the results obtained from the programs using the same element were found to be practically identical. Zal et al. [197] introduced a technique involving FEA simulation to model the press forming process of PVC-based composite laminates and fiber metal laminates. These laminates were reinforced with woven glass fabrics using various layup configurations, including [0/90]6, [45/−45]6, [0/90, 0/90, Al], and [45/−45, 45/−45, Al].

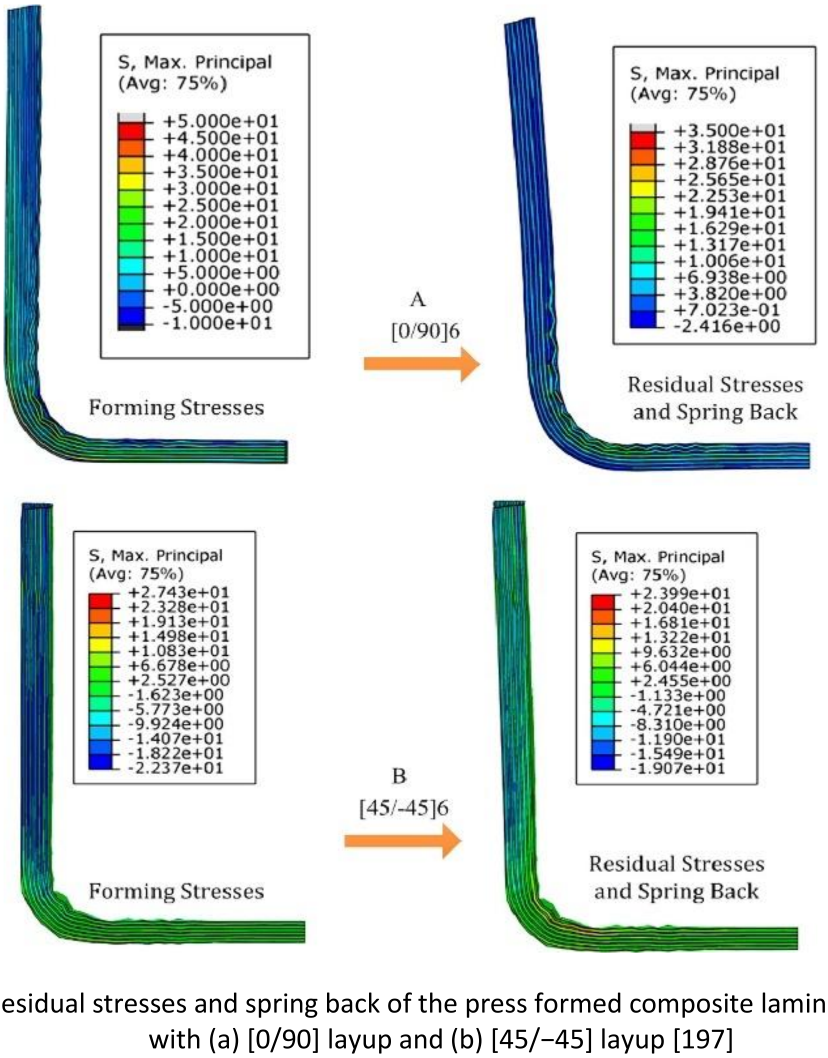


Fig. 15. Residual stresses and spring back of the press formed composite laminates at 160 °C with (a) [0/90] layup and (b) [45/−45] layup [197]

Springback primarily occurs due to the discharge of stored elastic energy and can result in undesired tolerance deviations in components during subsequent assembly [198]. Modifying the conditions of the forming process can help mitigate the extent of springback. For instance, it is widely recognized that applying a controlled level of in-plane stretching can effectively minimize springback following bending. By employing a precise constitutive model alongside FEA simulations, it becomes possible to conduct efficient and swift simulations of the forming process and springback, enabling the design of die tooling that compensates for springback, while remaining cost-effective.

In contrast, crystal plasticity-based constitutive models present an alternative approach. Nevertheless, their utilization for predicting springback is infrequently documented in literature due to the numerical simplicity and computational efficiency of phenomenological plasticity models. Figure 16 show the residual stress distribution as a function of depth in the CFRP/steel/CFRP component.

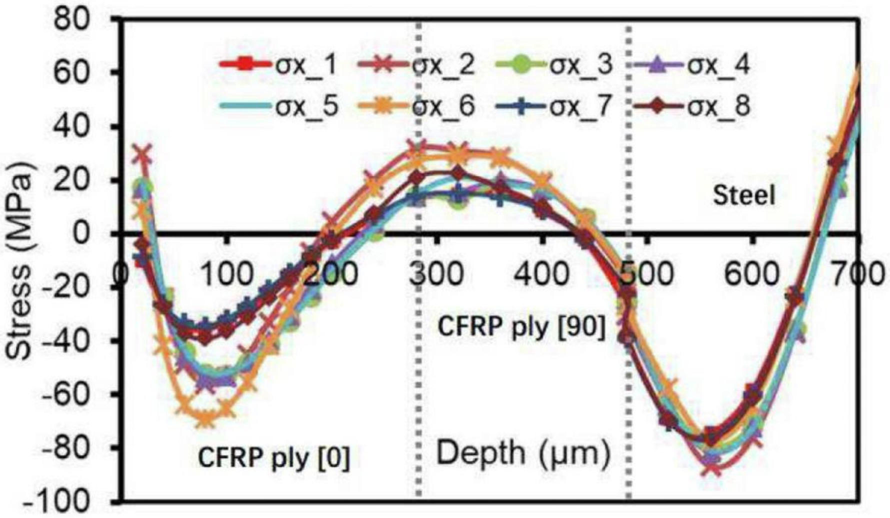


Fig. 16. Residual stresses across the thickness of the FMLs [199]

Frequently, type I crystal plasticity finite element models (CP-FEM) are primarily employed to derive the homogenized properties of polycrystalline aggregates represented by the finite element mesh [200]. Figure 17 shows springback simulation with the two symmetric planes, while Figure 18 (a) depicts profiles of distribution of von mises, and Figure 18 (b) shows the prediction of springback angles. Their utilization typically revolves around solving straightforward boundary-value problems, rather than being applied to industrial finite element forming operations or large-scale structures [201–206].

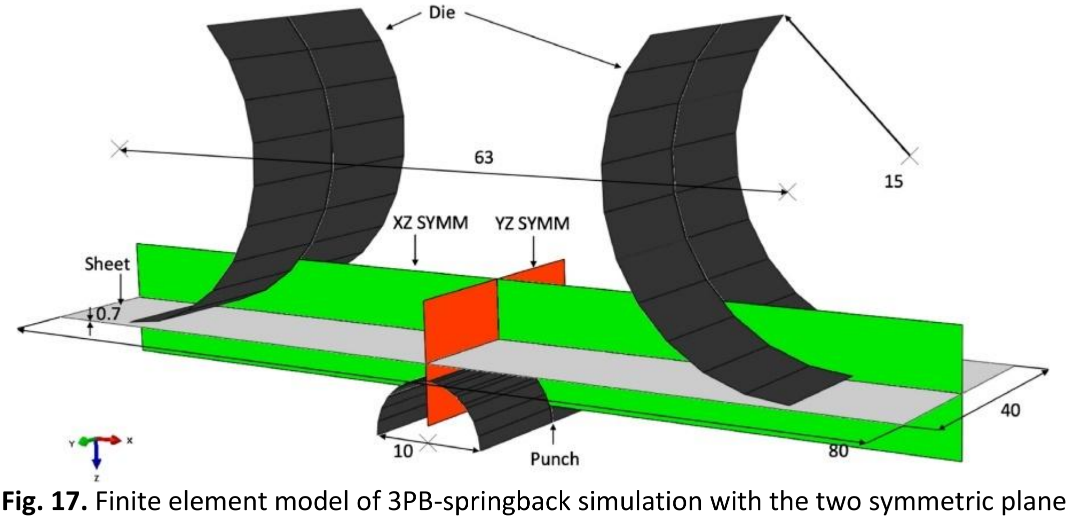
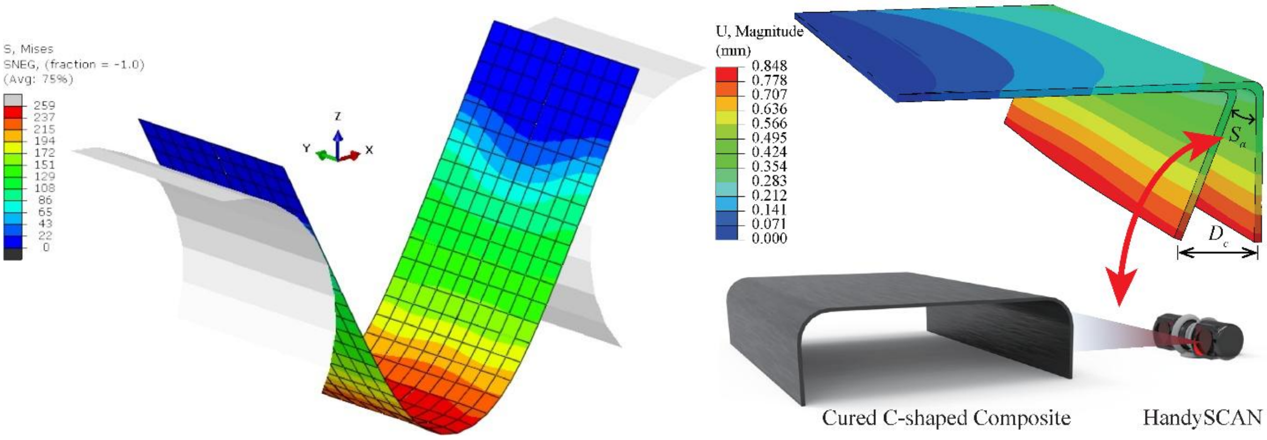


Fig. 17. Finite element model of 3PB-springback simulation with the two symmetric planes labelled as XZ SYMM and YZ SYMM in red and green [207]



(a) (b)

Fig. 18. (a) Springback profiles of distribution of von Mises [207]; **(**b) The prediction for the spring-back angle of the composites with a [0/90]4S layup, along with the schematic of the laser scanning experiment [208]

In general, mathematical models [209, 210] or simulations can be utilized to forecast the spring-back angle of composites. Ali and Chatti [211] created a mathematical model to anticipate the springback phenomenon in the air bending process of a thick sandwich panel composed of steel, polyurethane (PUR), and steel. Futhermore, Li and Hu [212] achieved the estimation of springback by employing both theoretical derivation and numerical simulation, which aligned with the experimental outcomes, deducing the conclusion that reduction of sheet springback can be achieved through the implementation of ultrasonic vibration. These predictions rely on the properties of the composite material and the parameters of the deformation. Such forecasts play a crucial role in comprehending composite behavior and enhancing the design and manufacturing procedures associated with them.

5. Conclusion

In this review, the techniques for assessing the formability and springback of metal sheet polymer core were well examined. It was noted that when solid sheet metals are incorporated into sandwich laminate structures with polymers, during forming and other operations, adjustments are made to modify the mechanical properties of the constituent materials. Moreover, many researchers concluded that the amount of springback in FML specimens increased along with the face sheet's thickness, and the polymer core thickness had little effect on springback. In addition, the primary discovery is that increasing the thickness of the foam core leads to a decrease in the amount of springback. To ensure reliable industrial applications of these sandwich laminates, it is necessary to their mechanical behavior but also their formability and springback characteristics. Furthermore, many results indicate that die opening has the most significant impact on springback, while the punch radius has least effect on it. Springback is a common phenomenon in polymer materials that can impact the accuracy of final product dimensions. It is important for designers to be aware of the potential for springback and take steps to minimize it during the manufacturing process. Incorporation of polymers into sandwich laminate structures alongside monolithic sheet metals brings about changes in the mechanical behavior of the constituent materials during forming and other processes. These FML sandwich demonstrate exceptional mechanical, thermal, and structural characteristics, thereby providing versatility in functionality. In conclusion, to enable successful industrial applications of these sandwich laminates, it is crucial to acquire a deeper understanding of their mechanical behavior, as well as their characteristics in forming and springback.

Author Contributions

Conceptualization, E.C.O. and M.A.; methodology, E.C.O. and M.A.; formal analysis, E.C.O. and M.A.; investigation, E.C.O. and M.A.; writing—original draft preparation, E.C.O. and M.A.; writing—review and editing, E.C.O. and M.A.; visualization, E.C.O. and M.A. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

Not applicable.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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