



Article

Cooperative Deformation Behavior and Its Influence on Wrinkling and Spring-Back in Hot-Stamped Al/CF/PEEK Hybrid Structures

Yan Lu ^{1,2}, Songsong Zhang ^{1,*}, Kaizhou Zhang ³, Jinsong Xiong ¹, Yong Luo ¹, Yibo Li ²  and Yong Zhang ⁴

¹ School of Big Data and Intelligent Engineering, Guizhou University of Commerce, Guiyang 550014, China; 202520003@gzcc.edu.cn (Y.L.); 201910820@gzcc.edu.cn (J.X.); 201710648@gzcc.edu.cn (Y.L.)

² School of Mechanical and Electrical Engineering, Central South University, Changsha 410083, China; yibo.li@csu.edu.cn

³ Guizhou Material Industry Technology Research Institute, Guiyang 550014, China; tri_boat@163.com

⁴ Institute of Special Equipment Technology, China National Heavy Machinery Research Institute Co., Ltd., Xian 710018, China; 18004879141@163.com

* Correspondence: 202410095@gzcc.edu.cn

Abstract

Thermoplastic fiber-metal hybrid structures have attracted increasing attention for lightweight structure applications owing to their high specific strength and damage tolerance. Al/CF/PEEK hybrid components are promising lightweight structures in which the aluminum alloy and CF/PEEK layers undergo coupled deformation during hot stamping. However, how the presence of the aluminum layer modifies the deformation behavior of CF/PEEK in hybrid component forming has not been systematically clarified, particularly regarding its influence on stress–strain response, wrinkling, and subsequent spring-back. This study investigates the deformation behavior of Al/CF/PEEK hybrid V-shaped components through comparative finite element analyses of monolithic aluminum, single-material CF/PEEK, and hybrid structures. The material flow and stress–strain responses of the aluminum and CF/PEEK layers are comparatively analyzed between the monolithic and hybrid configurations, followed by an examination of the wrinkling behavior of CF/PEEK and Al/CF/PEEK and the spring-back responses of monolithic aluminum and the hybrid structure. The results show that, during the hot-stamping stage, the hybrid structure exhibits an S-shaped deformation pattern similar to that of monolithic aluminum, while the aluminum layer constrains the bending and fiber-direction shear deformation of the CF/PEEK layers. This constraint reduces the bending amplitude and shear deformation of CF/PEEK and consequently mitigates wrinkle formation. During the subsequent cooling stage, the differences in the coefficients of thermal expansion, elastic modulus, and crystallization-induced shrinkage between aluminum and CF/PEEK result in different free contraction tendencies. Because the two layers remain mechanically coupled during cooling, this mismatch results in mutual constraint and stress redistribution, leading to a reverse S-shaped residual stress distribution. The resulting residual stress state partially counteracts the spring-back tendency and reduces the spring-back deformation of the hybrid component. These results clarify how aluminum–CF/PEEK interaction modifies the deformation and stress–strain states of the constituent layers and thereby affects wrinkling and spring-back in thermoplastic fiber-metal hybrid structures.

Keywords: composites; hot stamping; deformation behavior; spring-back; wrinkling



Academic Editor: Luis Filipe Menezes

Received: 13 August 2026

Revised: 16 September 2026

Accepted: 22 September 2026

Published: 25 September 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and

conditions of the [Creative Commons](https://creativecommons.org/licenses/by/4.0/)

[Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Thermoplastic fiber-metal hybrid laminates (thermoplastic FMLs), composed of thin metal sheets and carbon fiber-reinforced thermoplastic composites (CFRTP), exhibit superior specific strength and stiffness, excellent fracture toughness, recyclability, and rapid forming cycle times. These advantages have led to their widespread application in aerospace [1], electric vehicles (EVs) [2], and high-speed marine vessels [3,4]. The one-step hot stamping process, as shown in Figure 1, involves stacking thin metal sheets with semi-finished CFRTP prepregs, heating to forming temperature, and then stamping and forming, simultaneously achieving metal–CFRTP bonding, forming, and cooling-induced crystallization within a single operation. This integrated process significantly improves manufacturing efficiency [5,6] and has become one of the most promising approaches for producing thermoplastic fiber-metal hybrid structures [7,8].

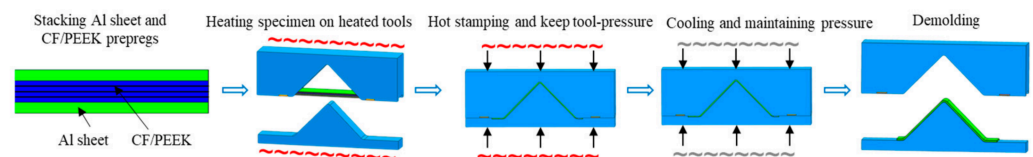


Figure 1. The one-step hot stamping forming process.

In the one-step hot stamping process, the thermoplastic resin is heated above its melting temperature. At this elevated temperature, the metal undergoes elastoplastic deformation while the CFRTP exhibits viscoelastic deformation [9,10]. Their significantly different deformation behaviors, coupled with distinct thermophysical properties (e.g., coefficients of thermal expansion, thermal conductivity), lead to several challenges, including deformation incompatibility between dissimilar materials, insufficient interlayer stress transfer, and high thermal residual stresses. Furthermore, the metal layer constrains the in-plane deformation of CFRTP, while the composite layer alters the strain localization and stress transfer behavior of the metal sheet during forming. These issues frequently result in severe spring-back, interfacial debonding, wrinkling and uneven thickness distribution. Current research on the forming performance of fiber-metal hybrid components primarily focuses on stress–strain distribution and wrinkling defects [8,11–14], dimensional accuracy [15,16], cracking [17,18] and spring-back deformation [19–21]. Although considerable efforts have been devoted to predicting forming defects, the underlying cooperative deformation mechanism between the metal and CFRTP layers has received far less attention.

Matthias M et al. [22] investigated the forming behavior of aluminum sheets and GFRP composites separately, providing insights into individual material deformation during FML manufacturing. However, such separated analyses cannot capture the coupled thermoforming behavior of hybrid laminates and the cooperative deformation mechanism between dissimilar materials remains poorly understood. Several investigations compared the deformation behavior of monolithic metallic, composite, and hybrid structures. Zhu X [23] experimentally compared the formability of metallic, CFRP, and hybrid structures, demonstrating that the CFRP layer affected the material flow of the metal layer and wrinkle formation. Nevertheless, the interaction between the constituent materials was evaluated only through macroscopic forming behavior. Quantitative characterization of the coupled material flow, stress redistribution, and cooperative deformation behavior during thermoforming was not achieved, leaving the underlying cooperative deformation mechanism unresolved.

Our previous studies have established the constitutive models [9], experimental basis [24], and thermoforming–cooling–spring-back simulation framework [20,25] for

CF/PEEK and Al/CF/PEEK hybrid structures. However, the role of the aluminum layer in modifying the deformation characteristics of CF/PEEK during hybrid forming has not been systematically clarified. It remains unclear how the presence of the aluminum layer modifies the deformation behavior and stress–strain states of CF/PEEK during hybrid forming and how these changes are related to wrinkle formation and subsequent spring-back behavior. To this end, the present study comparatively investigates monolithic Al, single-material CF/PEEK, and Al/CF/PEEK hybrid V-shaped components under the same forming configuration. The material flow behavior during hot stamping is first characterized for the monolithic Al component and then comparatively examined among the Al and CF/PEEK monolithic components and the corresponding Al and CF/PEEK layers in the hybrid structure. The stress and strain states after forming are subsequently compared for the Al and CF/PEEK layers, with particular attention to the shear strain response of CF/PEEK. The wrinkling behavior of CF/PEEK and Al/CF/PEEK is then compared to investigate the effect of the aluminum layer on wrinkle formation. Finally, the spring-back responses of monolithic Al and Al/CF/PEEK are compared to examine the influence of the hybrid configuration on the final shape after cooling. These comparisons aim to clarify the role of the aluminum layer in the deformation and stress responses of the hybrid structure and to establish their relationship with the wrinkling and spring-back behavior of Al/CF/PEEK hybrid V-shaped components. These findings provide mechanistic insights into defect suppression and offer guidance for the design and optimization of thermoplastic fiber-metal hybrid structures.

2. Materials and Methods

2.1. Materials

This study utilized T700 unidirectional CF/PEEK prepregs produced by Evonik Industries AG (Essen, Germany), with a thickness of 0.14–0.16 mm, a density of 1.58 g/cm³, a fiber volume fraction of 60%, and glass transition temperature (T_g) and melting temperature (T_m) of 145 °C and 345 °C, respectively. A highly ductile 2024-O aluminum alloy with 0.8 mm thickness was employed.

Unless otherwise specified, all analyses presented in this study are based on [Al/0/0/0/0]_S and [0/0/0/0/0]_S laminates. Only the wrinkling analysis (Section 3.3) employs the [Al/±45/±45]_S and [±45/±45]_S layups, because these layups are more suitable for revealing fiber shear deformation and wrinkle formation during thermoforming.

2.2. Constitutive Models

Based on our previous study [20], the strain rate–temperature-dependent deformation behavior of aluminum alloy during forming was characterized using the Norton–Hoff constitutive model:

$$\sigma = K \cdot \varepsilon^{n_1} \cdot \dot{\varepsilon}^{n_2} \cdot \exp^{\beta/T} \quad (1)$$

where K , n_1 , n_2 , and β are model parameters, T is temperature, ε is strain, and $\dot{\varepsilon}$ is the strain rate.

Based on our previous study [9], the rate–temperature-dependent visco-hyperelastic constitutive model was employed to characterize the forming behavior of unidirectional CF/PEEK:

$$\left\{ \begin{array}{l}
\psi(\mathbf{C}_{\mathbf{e}i}, \mathbf{C}, T, \kappa) = \psi_{\text{matrix}}(\mathbf{C}_{\mathbf{e}1}, T, \kappa) + \psi_{\text{shear}}(\mathbf{C}_{\mathbf{e}2}, T, \kappa) + \psi_{\text{fiber}}(\mathbf{C}) \\
\psi_{\text{matrix}}(\mathbf{C}_{\mathbf{e}1}, T, \kappa) = \left[C_{10}(\bar{I}_1^{e1} - 3) + \frac{1}{D}(J - 1)^2 \right] \cdot f_m(T) \cdot f_m(\kappa) \\
\psi_{\text{shear}}(\mathbf{C}_{\mathbf{e}2}, T, \kappa) = [\exp(c_1 I_{sh}) \cdot (c_2 I_{sh}^4 + c_3 I_{sh}^2)] \cdot f_s(T) \cdot f_s(\kappa) \\
\psi_{\text{fiber}}(\mathbf{C}) = \frac{g_1}{2g_2} \exp[g_2(I_4 - 1)^2 - 1] \\
\mathbf{S} = 2\mathbf{F}_{\mathbf{v}1}^{-1} \cdot \frac{\partial \psi_{\text{matrix}}}{\partial \mathbf{C}_{\mathbf{e}1}} \cdot \mathbf{F}_{\mathbf{v}1}^{-T} + 2\mathbf{F}_{\mathbf{v}2}^{-1} \cdot \frac{\partial \psi_{\text{shear}}}{\partial \mathbf{C}_{\mathbf{e}2}} \cdot \mathbf{F}_{\mathbf{v}2}^{-T} + 2 \frac{\partial \psi_{\text{fiber}}}{\partial \mathbf{C}} \\
\boldsymbol{\sigma} = \frac{1}{J} \mathbf{F} \cdot \mathbf{S} \cdot \mathbf{F}^T \\
= \frac{2}{J} \left[\mathbf{F}_{\mathbf{e}1} \cdot \sum_{k=1}^5 \left(\frac{\partial \psi_{\text{matrix}}}{\partial I_k^{e1}} \cdot \frac{\partial I_k^{e1}}{\partial \mathbf{C}_{\mathbf{e}1}} \right) \cdot \mathbf{F}_{\mathbf{e}1}^T + \mathbf{F}_{\mathbf{e}2} \cdot \sum_{m=1}^5 \left(\frac{\partial \psi_{\text{shear}}}{\partial I_m^{e2}} \cdot \frac{\partial I_m^{e2}}{\partial \mathbf{C}_{\mathbf{e}2}} \right) \cdot \mathbf{F}_{\mathbf{e}2}^T + \mathbf{F} \cdot \sum_{n=1}^5 \left(\frac{\partial \psi_{\text{fiber}}}{\partial I_n} \cdot \frac{\partial I_n}{\partial \mathbf{C}} \right) \cdot \mathbf{F}^T \right] \\
= \frac{2}{J} \{ W_1^{e1} \cdot \mathbf{B}_{\mathbf{e}1} + W_3^{e1} I_3^{e1} \cdot \mathbf{I} + W_4^{e2} \cdot \mathbf{a}_2 \otimes \mathbf{a}_2 + W_5^{e2} \cdot (\mathbf{a}_2 \otimes \mathbf{B}_{\mathbf{e}2} \mathbf{a}_2 + \mathbf{a}_2 \mathbf{B}_{\mathbf{e}2} \otimes \mathbf{a}_2) + W_4 \cdot \mathbf{a} \otimes \mathbf{a} \} \\
\mathbf{F}_{\mathbf{v}i}^r = \lambda_{eq}^{vi} \cdot \mathbf{F}_{\mathbf{e}i}^{-1} \cdot \frac{\boldsymbol{\sigma}}{\|\boldsymbol{\sigma}\|} \cdot \mathbf{F}_{\mathbf{e}i}, \mathbf{F}_{\mathbf{v}i} = \mathbf{F}_{\mathbf{v}i}^r \cdot \Delta t / 2 \\
\lambda_{eq}^{vi} = \text{Asinh}(B' \sqrt{\boldsymbol{\sigma} : \boldsymbol{\sigma}}) n, I_{sh} = I_5^2 - I_4^2
\end{array} \right. \quad (2)$$

The unidirectional CF/PEEK was considered as a linear elastic solid exhibiting transverse isotropy during cooling crystallization; an elastic constitutive model was applied [20]:

$$\mathbf{S} = \boldsymbol{\Gamma} : \mathbf{E}, \mathbf{E} = \boldsymbol{\varepsilon} - (\boldsymbol{\alpha} + \boldsymbol{\beta}) \cdot \Delta T \quad (3)$$

where $\boldsymbol{\Gamma}$ is the fourth-order elasticity tensor composed of engineering constants. $\mathbf{S}$ is the Second Piola-Kirchhoff stress tensor; $\mathbf{E}$ is the Green–Lagrange effective strain tensor; $\boldsymbol{\varepsilon}$ is the total strain tensor; $\boldsymbol{\alpha}$ is the thermal expansion coefficient tensor; $\boldsymbol{\beta}$ is the crystallization shrinkage coefficient tensor (exists only in the transverse direction of unidirectional CF/PEEK); and ΔT is the temperature change.

During the cooling process of CF/PEEK, the heat released by PEEK crystallization is incorporated as an additional heat source term in the heat conduction equation and expressed as [26]:

$$\begin{aligned}
q_v &= \rho V H^{cryst} \frac{dX_t}{dt} \\
H^{cryst}(t) &= \int_{t_0}^t Q^{cryst}(t^*) dt^*
\end{aligned} \quad (4)$$

where ρ is the density of CF/PEEK, V is the element volume of CF/PEEK, H^{cryst} is the crystallization enthalpy, Q^{cryst} is the heat flow, and t_0 is the time at the onset of crystallization.

To describe the non-isothermal crystallization kinetics of PEEK, a modified Avrami equation is adopted to calculate the relative crystallinity [27]:

$$1 - X_t = \exp(-Z_t t^n) \quad (5)$$

where Z_t is the rate constant for the non-isothermal crystallization process, and n is the Avrami exponent.

The material parameters were taken from our previous studies [9,20,28], where the corresponding constitutive models were independently calibrated and validated for the thermoforming of Al/CF/PEEK structures.

2.3. Finite Element Models

Figure 2 displays the Abaqus finite element model for aluminum alloy (Al) V-shaped parts. The Al sheets were discretized with a mesh size of 1 mm (C3D8RT), and there were 2 elements in the thickness direction. The material properties were represented in a user-defined VUMAT. The tools (die and punch) were set as rigid bodies, and the

initial temperature of the blank was set at 350 °C. The interfacial friction coefficient of 0.1 was chosen.

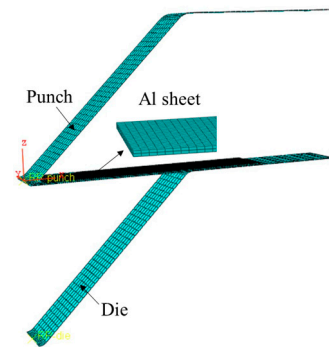


Figure 2. The FE model of the Al V-shaped parts.

For the monolithic Al V-shaped component, the experimental procedure follows the conventional hot-forming and spring-back sequence. After hot stamping, the component is immediately unloaded from the die and subsequently allowed to cool freely in air to room temperature. Therefore, cooling occurs after unloading rather than under die constraint, and the residual stress state relevant to the unloading-induced spring-back is the forming-induced residual stress state at the end of hot stamping. Because cooling occurs after unloading and under free-air conditions, it is not treated as a constrained thermo-mechanical step in the spring-back simulation. In ABAQUS, the geometry, mesh, and residual stress field at the end of forming are directly transferred to the spring-back model as the initial state, and the spring-back calculation is then performed by applying the corresponding symmetry-plane boundary condition.

In the Abaqus/Explicit module, the finite element model of one-step hot stamping forming of single-material CF/PEEK V-shaped parts was established, as shown in Figure 3. The sample size was 240 mm × 25 mm × 0.14 mm, which was discretized with a mesh size of 1 mm (S4R). The model material was defined by a VUMAT subroutine. Other boundary conditions were similar to the stamping model of Al V-shaped parts. According to the interface sliding friction test results [20], the friction coefficient between prepreg and tools was set to be 0.4, and the friction coefficient between prepreg layers was set to be 0.34.

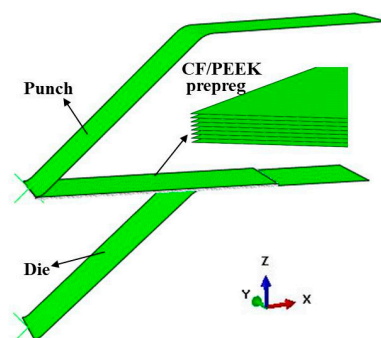


Figure 3. The FE model of the CF/PEEK V-shaped parts.

References [20,29] demonstrated that the molten CF/PEEK composite is nearly stress-free during hot stamping, and the residual stress generated during cooling within closed tools is negligible. For single-material CF/PEEK V-shaped components cooled under closed-die conditions, the temperature gradient across the thickness is minimal [9]. Moreover, because all eight CF/PEEK plies are aligned in the 0° fiber direction, adjacent plies have the same fiber orientation and therefore exhibit similar thermal expansion and stiffness responses along the fiber direction. Consequently, no significant interlaminar mismatch

associated with different ply orientations is expected during cooling. For the V-shaped Al/CF/PEEK components with this 0° lay-up, our previous study [20] revealed that the fiber-direction stress dominates the spring-back behavior, whereas the contribution of the transverse stress is negligible. Therefore, the spring-back of the single-material CF/PEEK V-shaped components with the same 0° lay-up can be considered negligible.

According to our previous studies [20,28], the forming process of the Al/CF/PEEK hybrid V-shaped part was simulated using ABAQUS/Explicit (Figure 4a). Because the hybrid component remains constrained during cooling before unloading, the subsequent cooling, thermo-mechanical stress, and spring-back analyses were sequentially performed using ABAQUS/Standard (Figure 4b,c). The temperature field obtained from the heat transfer analysis was first used to calculate the residual stress field after cooling to room temperature. During the cooling simulation, the Al and CF/PEEK layers were connected using a Tie constraint, representing a perfectly bonded interface. Therefore, relative displacement between the two layers was constrained during cooling, ensuring deformation compatibility across the interface. Due to the differences in coefficients of thermal expansion, elastic modulus, and crystallization-induced shrinkage between Al and CF/PEEK, their free contraction tendencies were different. Under the interfacial constraint, this mismatch in free contraction resulted in mutual constraint and stress transfer between the two layers, thereby redistributing the residual stresses before unloading. This residual stress field was then imported as a predefined field into the spring-back model as the initial state.

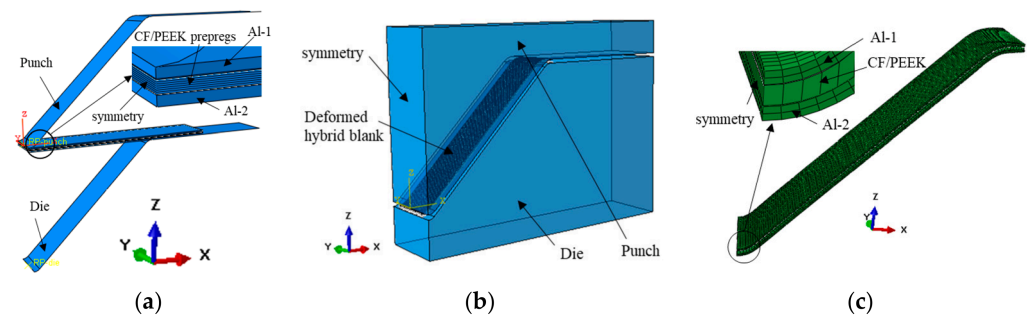


Figure 4. FE model for Al/CF/PEEK hybrid V-shaped parts: (a) FE model of one-step hot stamping forming; (b) FE model of transient heat transfer; (c) FE model of thermal stress and spring-back calculation during cooling process.

2.4. Validation of the Aluminum Alloy Model

Aluminum alloy V-shaped components ($240 \text{ mm} \times 25 \text{ mm} \times 0.8 \text{ mm}$) were fabricated under six forming conditions combining two temperatures (350 and 380°C) and three stamping speeds (5 , 10 , and 20 mm/s). These processing conditions were identical to those used for the Al/CF/PEEK hybrid V-shaped components in our previous study, enabling a direct comparison of the thermoforming behavior and cooperative deformation characteristics between monolithic and hybrid structures. After forming, the specimens were immediately unloaded from the die and allowed to cool freely in air to room temperature. The spring-back angle of each specimen was measured three times and averaged for model validation.

Our previous studies [9,20] validated the thermoforming models for CF/PEEK and Al/CF/PEEK hybrid V-shaped components through comparisons of profile geometry, stamping load, cooling history, and spring-back deformation. Therefore, only the aluminum alloy constitutive model is further validated in this study. As shown in Figure 5b,c, the aluminum alloy V-shaped components exhibited significant spring-back under all forming conditions. The simulated spring-back angles agreed well with the experimen-

tal measurements, with the smallest spring-back obtained under the 380 °C/5 mm·s⁻¹ condition, confirming the predictive capability of the constitutive model.

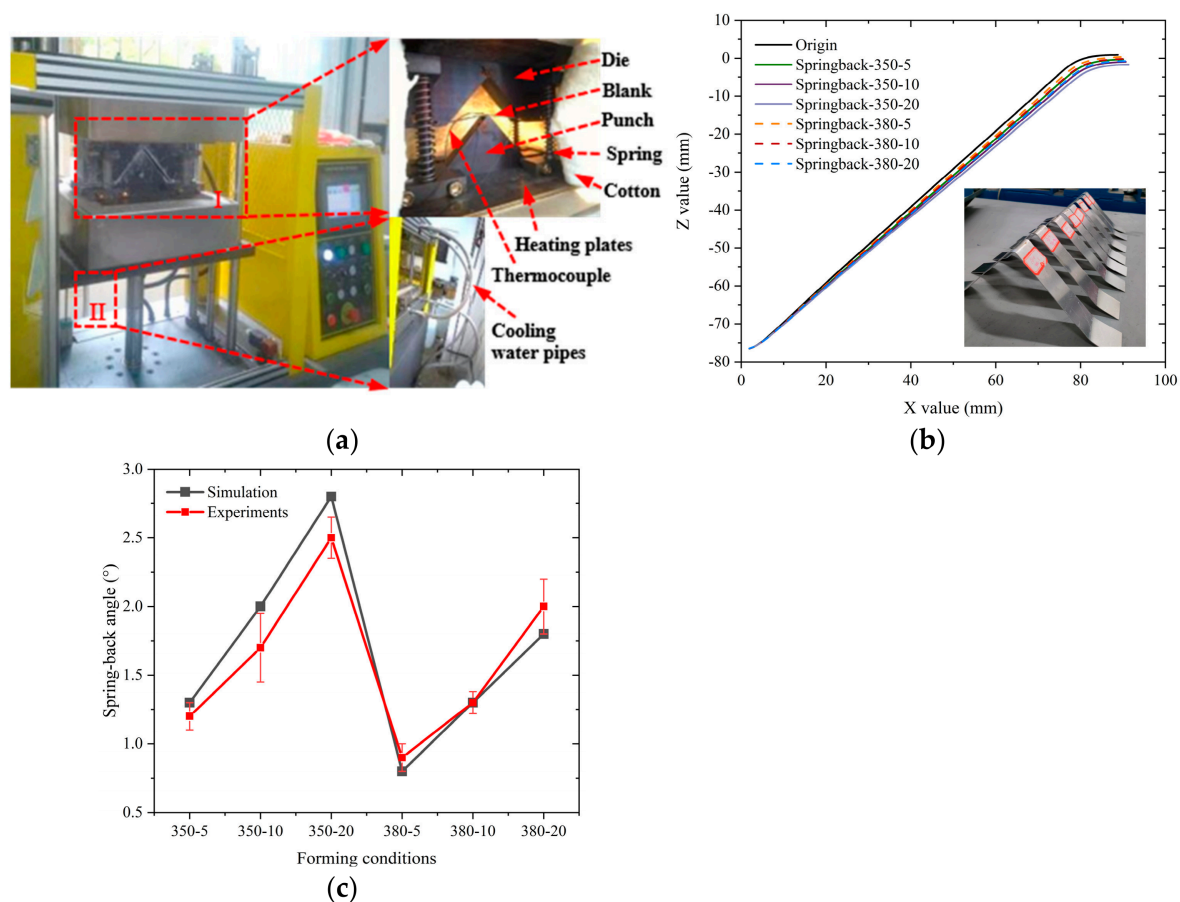


Figure 5. Simulation and experimental results of spring-back for aluminum alloy V-shaped parts: (a) experiment set-up; (b) shape change in V-shaped part after spring-back; (c) comparison of spring-back angle.

3. Results and Discussion

3.1. Cooperative Deformation Mechanism

3.1.1. Thermoforming Behavior of Monolithic Aluminum

Figure 6 shows the material flow velocity vector diagram and corresponding stress contour plot during the hot stamping process of aluminum alloy sheet at a forming temperature of 350 °C and stamping speed of 5 mm/s. Figure 6 indicates that during thermoforming, the aluminum alloy initially undergoes three-point bending, followed by sliding along the die surface. As the punch approaches the bottom dead center, a characteristic S-shaped deformation develops between the punch and die, producing two pairs of reverse-curved bending regions (A/D and B/C). After complete die closure, the material fully conforms to the die cavity and the temporary S-shaped deformation disappears. These deformation characteristics provide a reference for understanding the interaction between the aluminum alloy and CF/PEEK layers in hybrid structures.

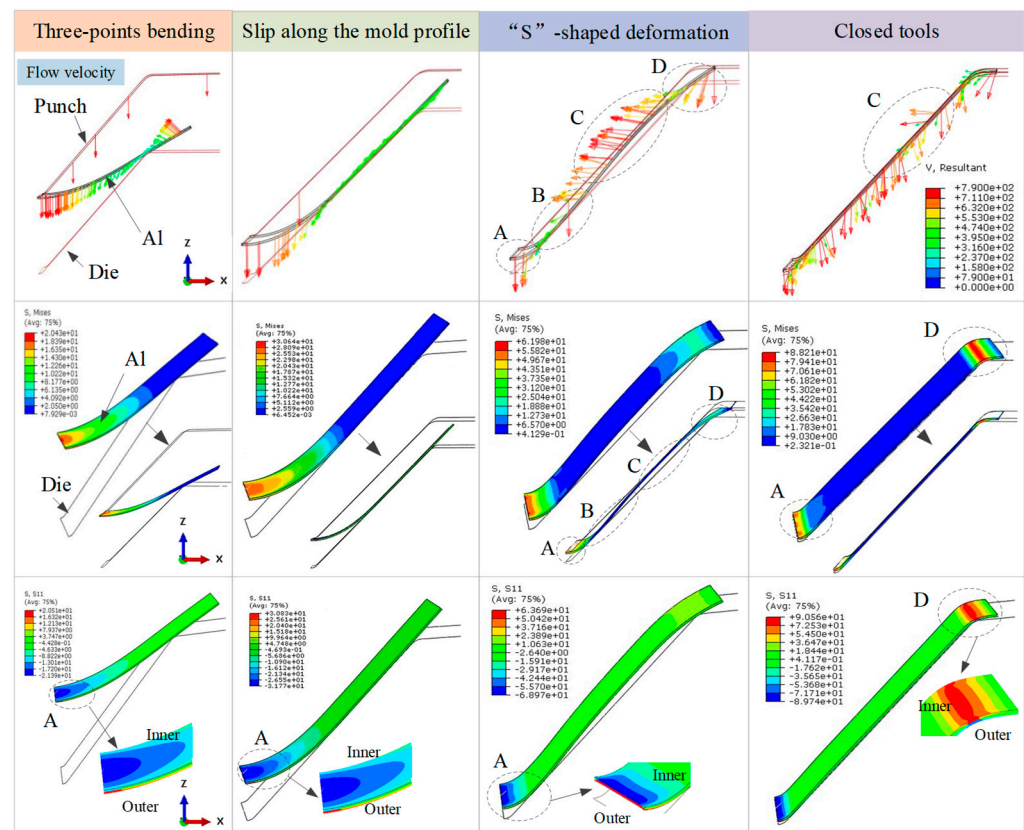


Figure 6. Flow behavior and stress analysis of aluminum alloy (Al) V-shaped parts during the stamping process.

The stress on the aluminum alloy increases with the punch stroke. After stamping formation, higher equivalent stress (S , Mises) appears in the central bending zone A and end bending zone D where deformation is more significant. The global X-direction stress (S , S11) can reflect the tensile ($S11 > 0$) and compressive ($S11 < 0$) stress states on the inner and outer surfaces of bending zones A and D in the aluminum alloy layer. In bending zone A, S11 is predominantly negative on the inner surface and positive on the outer surface, whereas the opposite distribution is observed in bending zone D, with positive S11 on the inner surface and negative S11 on the outer surface. This opposite through-thickness stress distribution between zones A and D is consistent with their reverse bending directions and reflects the formation of two oppositely curved regions during the S-shaped deformation of the aluminum V-shaped component. The opposite tensile–compressive stress states generated in the two reverse-curved regions indicate that the temporary S-shaped deformation dominates stress redistribution during thermoforming, which subsequently influences the deformation compatibility between constituent materials in hybrid structures.

3.1.2. Comparison with Single-Material and Hybrid Structures

Figure 7 presents a comparative analysis of the flow velocities and flow directions among: (1) the aluminum alloy layer (Al-1) in contact with the punch and the fourth intermediate CF/PEEK prepreg layer in Al/CF/PEEK hybrid V-shaped components, (2) the aluminum sheet (Al) in Al V-shaped components, and (3) the CF/PEEK layer in CF/PEEK V-shaped components—under forming conditions of 350 °C and 5 mm/s at varying punch stroke positions.

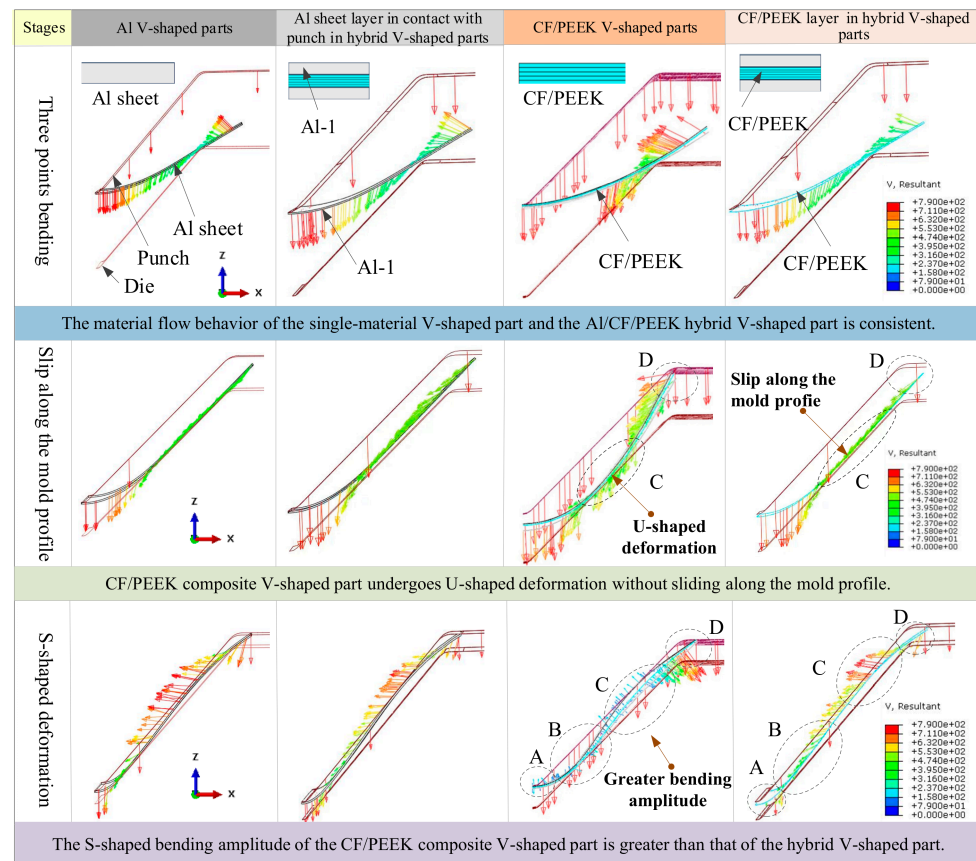


Figure 7. Comparison of material flow behavior between Al/CF/PEEK hybrid V-shaped parts and single-material V-shaped parts.

Figure 7 shows that in the initial stage, both the Al/CF/PEEK hybrid V-shaped components and the single-material V-shaped components exhibit identical flow behavior, manifesting as three-point bending deformation. During the intermediate stage, the Al/CF/PEEK hybrid V-shaped components demonstrate similar flow patterns to the Al V-shaped components, both sliding along the die surface. However, the CF/PEEK V-shaped components form a U-shaped deformation between the punch and die. This occurs because the bending modulus of CF/PEEK in its molten state is significantly lower than that of aluminum alloy, making it more prone to bending deformation under stamping forces. In the final stage, all materials develop an S-shaped deformation between the tools, with the difference being that the CF/PEEK V-shaped components exhibit more pronounced bending amplitude in their S shape compared to both the Al/CF/PEEK hybrid V-shaped components and Al V-shaped components. These results indicate that the aluminum alloy layer governs the overall deformation path of the hybrid structure and constrains the bending deformation of the molten CF/PEEK layer along the fiber direction, resulting in a reduced S-shaped bending amplitude and laying the foundation for the subsequent stress redistribution during thermoforming.

3.2. Stress Evolution Governing Cooperative Deformation

3.2.1. Stress Evolution Monolithic Aluminum

The subroutine employs state variable SDV1 to track the equivalent plastic strain of the aluminum alloy during the forming process. Figure 8 shows that the equivalent plastic strain is mainly concentrated in bending zones A and D, with the highest value occurring in zone A owing to its smaller bending radius. The equivalent stress exhibits a similar distribution, whereas the straight beam region experiences little deformation. The S11

distribution indicates a typical bending stress state in zone A, characterized by compression on the inner surface and tension on the outer surface.

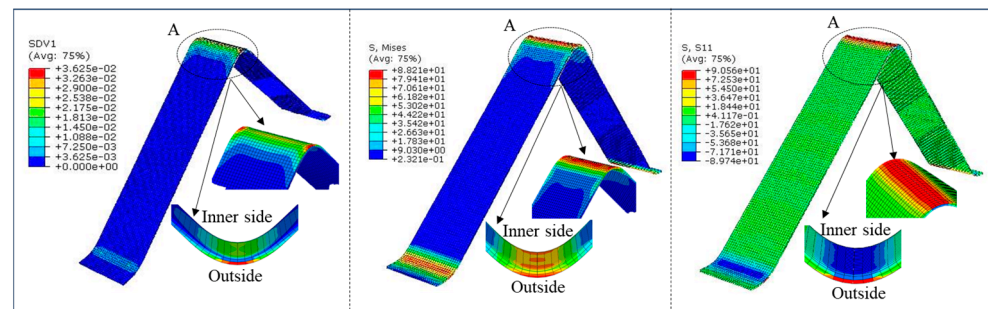


Figure 8. Equivalent plastic strain and stress contours of aluminum alloy (Al) V-shaped part.

To investigate the influence mechanism of forming process parameters on the S-shaped deformation of Al V-shaped components, Figure 9 compares the stress and strain distributions along typical path 1 under different process parameters. Figure 9a,b show that at a forming temperature of 350 °C, both the magnitude and increasing rate of stress in bending zone A are greater than those in bending zone D, and the stress difference between these two bending zones increases with stamping speed, indicating a more pronounced S-shaped deformation and a greater potential for spring-back after unloading. However, the stresses in bending zones B and C of the aluminum alloy V-shaped component are less affected by stamping speed. When the forming temperature is 380 °C, the stress difference between bending zones A and D under various stamping speeds is significantly smaller than that in the 350 °C specimens, demonstrating that elevated temperatures mitigate the S-shaped deformation and are therefore expected to reduce spring-back.

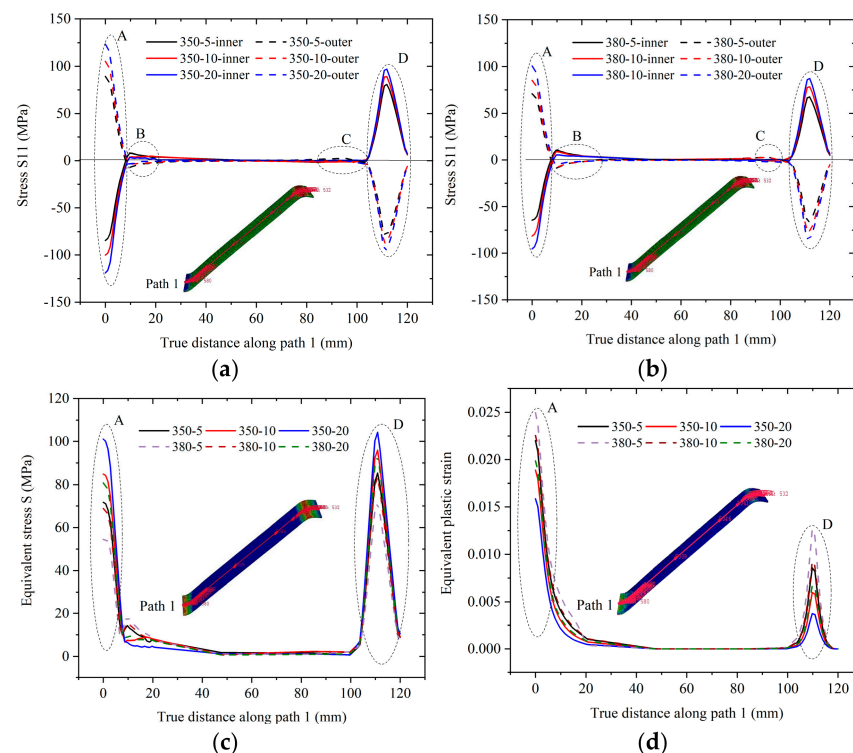


Figure 9. The stress and strain on Path 1 for aluminum alloy V-shaped parts under different process parameters: (a) the S11 of the Al sheet at 350 °C; (b) the S11 of the Al sheet at 380 °C; (c) the equivalent stress of the Al sheet; (d) the equivalent plastic strain of the Al sheet.

Furthermore, it was also observed that the stresses in the Al V-shaped components (both S11 and equivalent stress S) increase with higher stamping speeds and decrease with elevated forming temperatures, while the equivalent plastic strain decreases with increased stamping speeds and rises with higher forming temperatures. These trends can be attributed primarily to the temperature- and rate-dependent deformation behavior of the aluminum alloy. At elevated temperatures and lower strain rates, the aluminum alloy exhibits reduced yield strength and greater plastic deformability, leading to lower stress levels and larger plastic strains (see Figure 9c,d). Higher temperatures and lower stamping speeds promote plastic deformation while reducing the stress level in the aluminum alloy, providing favorable deformation characteristics for comparison with hybrid structures. Therefore, the stress and plastic strain evolution of the monolithic aluminum component provides the baseline for understanding the cooperative deformation behavior of hybrid structures.

The S11 and von Mises stress contours show similar spatial distributions (Figure 6), and their profiles along Path 1 exhibit comparable stress levels and consistent variation trends (Figure 9). Therefore, S11 was selected as the representative stress component for the subsequent analysis. Regions A and D are located in the two main bending regions of the V-shaped component, where the residual stresses are relatively high, whereas the stress levels in regions B and C are comparatively low. Therefore, the S11 stress difference between A and D was used to characterize the residual-stress imbalance between the two main bending regions and to assist in interpreting the spring-back tendency.

3.2.2. Comparison of Stress and Strain Evolution in Single-Material and Hybrid Structures

Figure 10 compares the inner and outer side stress S11, equivalent stress S, and equivalent plastic strain (SDV1) among: (1) the aluminum alloy layer in contact with the punch (Al-1) and die (Al-2) in Al/CF/PEEK hybrid V-shaped components, (2) the aluminum sheet (Al) in Al V-shaped components at a forming temperature of 350 °C and a stamping speed of 5 mm/s. Figure 10 shows that the stress states of the two types of V-shaped parts are consistent, with the stress and plastic strain of the Al V-shaped part being closer to those of the Al-2 layer in contact with the die. The close agreement between the stress distributions of the monolithic aluminum component and the aluminum layers in the hybrid structure indicates that the global deformation of the hybrid component is primarily governed by the aluminum alloy. This observation is consistent with the material flow analysis in Section 3.1, confirming that the aluminum alloy layer governs not only the flow velocity field but also the stress and plastic strain evolution during thermoforming.

Representative CF/PEEK prepreg layers adjacent to the punch (Layer 1) and die (Layer 8) were selected because they exhibit the maximum shear strain and equivalent stress, respectively. Figure 11a,b shows that, in the central bending zone A, the equivalent stress and shear strain of the prepreg layers in the Al/CF/PEEK hybrid V-shaped part are both smaller than those in the single-material CF/PEEK V-shaped part. This is because the aluminum alloy layer constrains the S-shaped bending deformation of the molten CF/PEEK layer, thereby reducing the deformation demand carried by the CF/PEEK. Meanwhile, the aluminum alloy layer intensifies interfacial sliding between the dissimilar materials, leading to non-uniform shear deformation in the hybrid component. Figure 11c presents the shear strain contour plots of the CF/PEEK layers in both the hybrid and CF/PEEK V-shaped parts, with larger shear strains concentrated in the central bending zone A. These results demonstrate that the aluminum alloy layer constrains the S-shaped bending deformation of the molten CF/PEEK layer through interfacial interaction, thereby controlling the deformation demand between the constituent materials. As a result, the CF/PEEK layer experiences lower equivalent stress and shear deformation while the hybrid structure retains a stress evolution pattern similar to that of monolithic aluminum. This

indicates that the aluminum alloy dominates the global deformation path, whereas the CF/PEEK layers modify the local deformation state through interlayer interaction, resulting in improved deformation compatibility between the two constituent materials. The reduced shear deformation in the CF/PEEK layers is expected to influence the subsequent wrinkling behavior, which is discussed in Section 3.3.

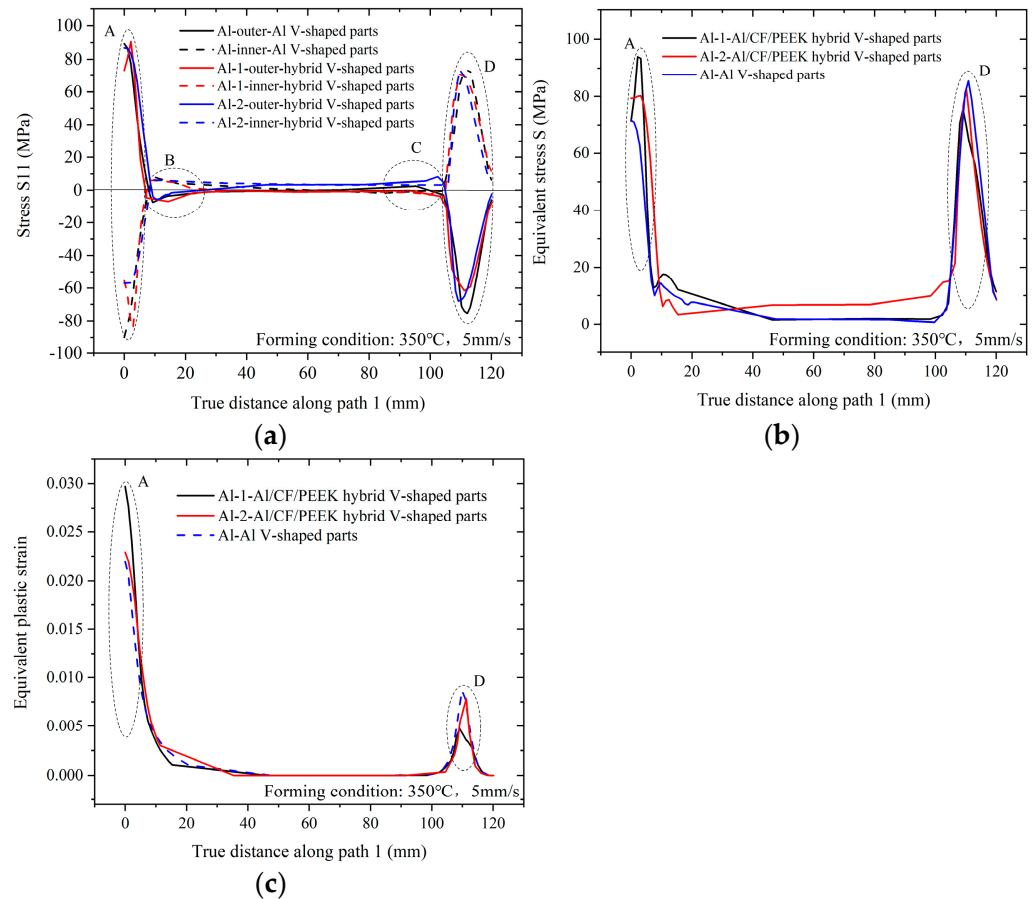


Figure 10. Comparison of stress and strain between the aluminum alloy layers (Al-1, Al-2) in Al/CF/PEEK hybrid V-shaped parts and the Al V-shaped parts (Al): (a) the S11 of the Al sheet; (b) the equivalent stress S of the Al sheet; (c) the equivalent plastic strain of the Al sheet.

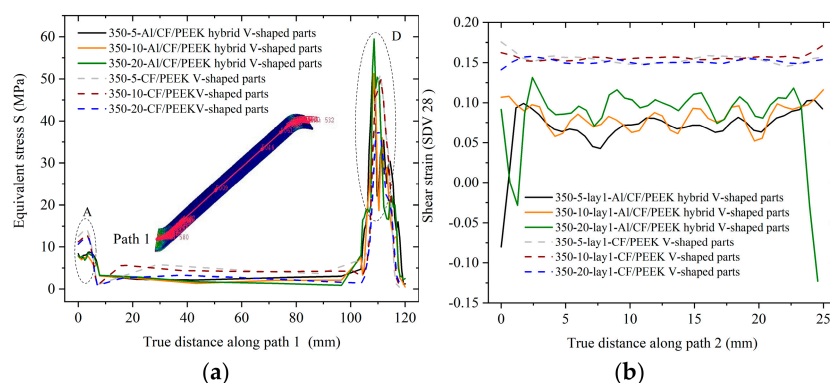


Figure 11. Cont.

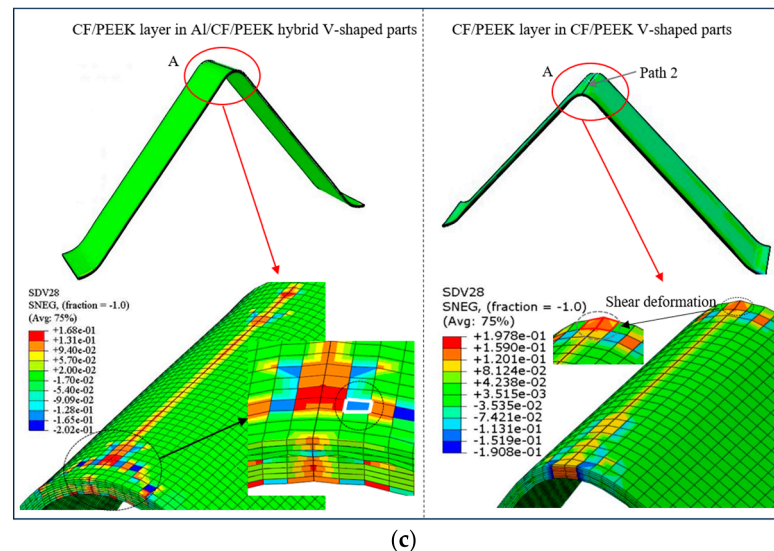


Figure 11. Comparison of shear strain between the CF/PEEK layer in Al/CF/PEEK hybrid V-shaped parts and the CF/PEEK V-shaped parts: (a) the equivalent stress S of the CF/PEEK layer; (b) the shear strain of the CF/PEEK layer; (c) the shear strain contours of the CF/PEEK layer.

3.3. Mechanism of Wrinkling Behavior

To better reveal the wrinkling mechanism governed by fiber shear deformation, the analyses in this section are performed using $[Al/\pm 45/\pm 45]_S$ and $[\pm 45/\pm 45]_S$ laminates. Figure 12 compares the material flow and shear strain during S-shaped deformation between the single-material CF/PEEK V-shaped part with a $[\pm 45/\pm 45]_S$ layup (left) and the Al/CF/PEEK hybrid V-shaped part with a $[Al/\pm 45/\pm 45]_S$ layup (right). The results show that the single-material CF/PEEK component exhibits pronounced shear deformation accompanied by fiber-direction warping, eventually leading to folding wrinkles in the end bending zone C. This behavior is associated with the relatively low bending stiffness of the molten CF/PEEK layer compared with the aluminum alloy [30]. Without the constraining effect of the aluminum layer, the CF/PEEK layer undergoes larger bending deformation during the S-shaped deformation of the V-shaped component, which is accompanied by greater in-plane shear deformation and fiber-direction warping. The resulting out-of-plane deformation develops into folding wrinkles in the end bending zone C. In contrast, no fiber warping or folding wrinkles are observed in the Al/CF/PEEK hybrid component. The aluminum alloy layer provides additional bending resistance and constrains the bending deformation of the molten CF/PEEK layer, thereby reducing its fiber-direction shear deformation and suppressing the associated out-of-plane deformation. Consistent with the $[Al/0/0/0/0]_S$ hybrid laminate, the $[Al/\pm 45/\pm 45]_S$ hybrid structure also exhibits significantly lower shear strain in the central bending zone A than the single-material CF/PEEK component. These observations suggest that the aluminum alloy layer plays an important role in regulating the S-shaped deformation of the molten CF/PEEK layer by limiting excessive fiber-direction shear deformation and enhancing deformation compatibility. Combined with the material flow and stress evolution analyses in Sections 3.1 and 3.2, the improved interlayer deformation coordination is considered a key factor contributing to wrinkle suppression during thermoforming.

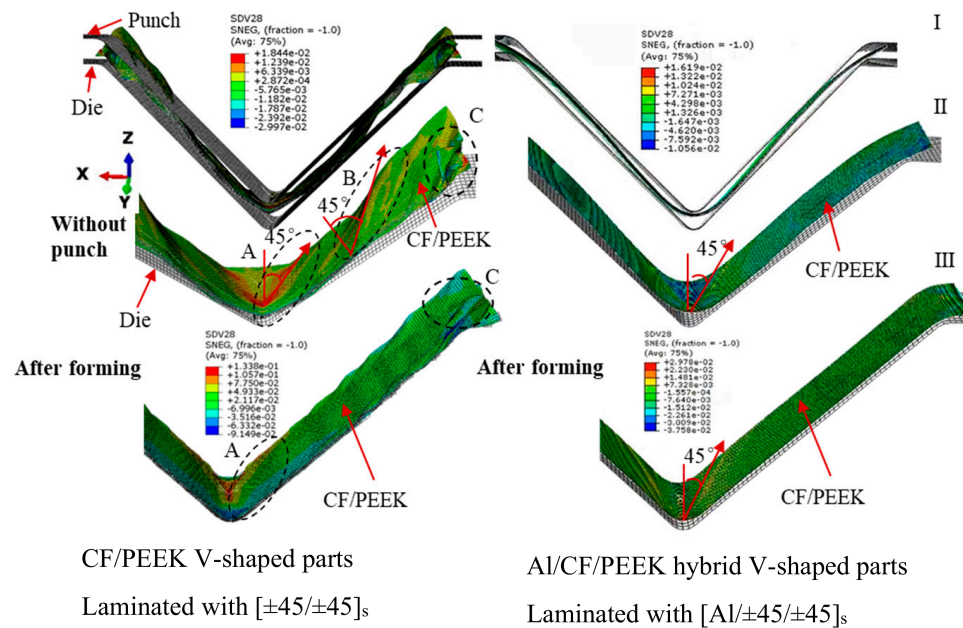


Figure 12. Comparison of wrinkling between the CF/PEEK layer in Al/CF/PEEK hybrid V-shaped parts and the CF/PEEK V-shaped parts.

3.4. Mechanism of Spring-Back Behavior

3.4.1. Spring-Back Behavior of Monolithic Aluminum During Thermoforming

Figure 13 presents the stress S11 distribution along typical path 1 on both the inner and outer sides of the Al V-shaped component under forming conditions of 350 °C and 5 mm/s, along with a schematic diagram showing the influence of tensile and compressive stress states in bending zones on spring-back. Figure 13 shows that bending zones A and C exhibit “compression on inner side and tension on outer side” stress states, while bending zones B and D show “tension on inner side and compression on outer side” stress states. According to sheet metal bending theory [28,31], after unloading, bending zones A and C undergo positive spring-back (bending angle > 90°), whereas bending zones B and D experience negative spring-back (bending angle < 90°). Since the stresses in bending zones B and C are relatively small, their influence on the spring-back of the V-shaped component can be neglected. The final spring-back direction and magnitude of the Al V-shaped component depend on the stress difference between the reverse bending zones A and D. If the absolute value of stress S11 in bending zone A is greater than that in bending zone D ($A-D > 0$), the component undergoes positive spring-back; otherwise, it experiences negative spring-back (spring-in). Clearly, under the forming conditions of 350 °C and 5 mm/s, the aluminum alloy V-shaped component shows $A-D > 0$, and therefore should exhibit positive spring-back after unloading.

The difference in the absolute values of stress S11 between bending zones A and D is therefore used to characterize the intensity of the S-shaped deformation. A larger stress difference corresponds to a more pronounced S-shaped deformation tendency and consequently a larger spring-back. This interpretation is consistent with the stress evolution discussed in Section 3.2, where increasing stamping speed and decreasing forming temperature enlarge the stress difference between bending zones A and D, corresponding to the larger spring-back angles observed experimentally in Figure 5c.

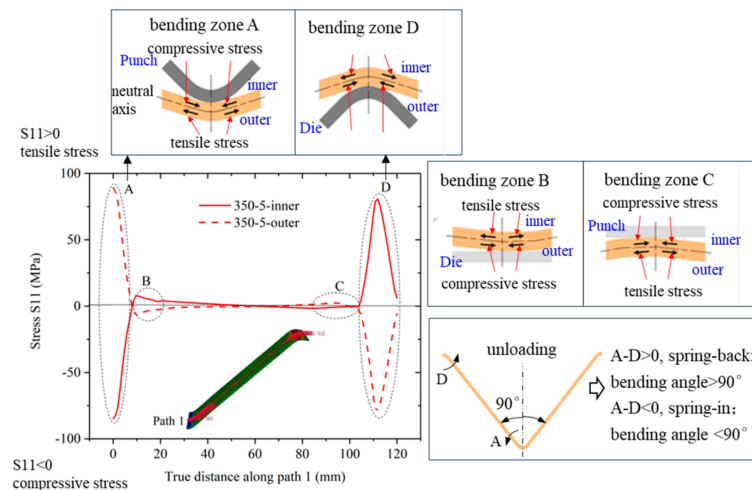


Figure 13. The S-shaped feature in aluminum alloy V-shaped parts and its influence on spring-back.

3.4.2. Comparison of Spring-Back Behavior in Monolithic Aluminum and Hybrid Structures

Figure 14 compares the experimental values of spring-back angles between Al V-shaped parts and Al/CF/PEEK hybrid V-shaped parts after unloading. The results show that the spring-back angles of Al V-shaped parts are consistently larger than those of hybrid V-shaped parts under all six forming processes. The aluminum alloy V-shaped parts were cooled in air, and it is considered that the temperature difference in the parts was small, generating no additional thermal stress. Therefore, the residual stress generated during stamping is the primary driving factor for the spring-back deformation of the Al V-shaped parts. However, due to the mismatch in the coefficients of thermal expansion, elastic modulus, and crystallization-induced shrinkage between the aluminum alloy and CF/PEEK layers, additional thermal stresses are generated in the Al/CF/PEEK hybrid V-shaped parts during cooling. This thermal stress, together with the residual stress from the aluminum alloy layer during stamping, collectively determines the spring-back deformation of the hybrid V-shaped parts.

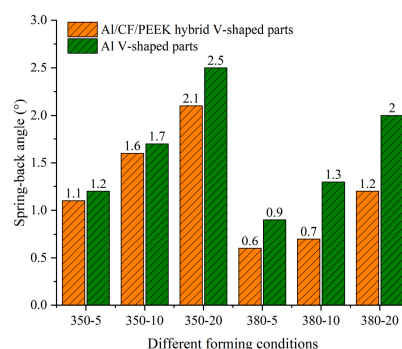


Figure 14. Comparison of spring-back between the Al/CF/PEEK hybrid V-shaped parts and the Al V-shaped parts.

Because the contribution of the CF/PEEK layer to the overall spring-back of the Al/CF/PEEK hybrid V-shaped parts is relatively small due to its small stress asymmetry between zones A and D and its high fiber-direction stiffness, as established in our previous study [20], the present analysis focuses on the residual stress distribution in the aluminum layer. To clarify the origin of the spring-back difference between aluminum and hybrid V-shaped structures, the residual stress distributions prior to unloading are further compared and quantified. Figure 15 compares the residual stresses before spring-back in the aluminum alloy layer of both Al V-shaped parts (Al) and Al/CF/PEEK hybrid V-shaped parts

(Al-1) under the forming conditions of 350 °C and 5 mm/s. As shown in Figure 15, due to the thermal mismatch, modulus mismatch, and inconsistent crystallization shrinkage, the aluminum alloy layer (Al-1) in the hybrid V-shaped part exhibits a higher absolute value of stress S_{11} in the outer bending zone A than in zone D after cooling, whereas the stress magnitude in the inner bending zone A is lower than that in zone D, resulting in a reverse S-shaped deformation. As established in Section 3.4.1, bending zones A and D undergo opposite bending directions and therefore produce opposite spring-back directions after unloading, whereas the effects of zones B and C are relatively small and can be neglected. Thus, the net spring-back response is governed by the relative contributions of the two oppositely bending zones A and D. For the hybrid structure, the stress differences between bending zones A and D are approximately 80 MPa on the outer surface and 60 MPa on the inner surface, but these differences act in opposite directions. Therefore, their net stress difference is approximately 20 MPa. In contrast, for the monolithic aluminum component, the stress differences between zones A and D are approximately 15 MPa and 14 MPa on the inner and outer surfaces, respectively, and they act in the same direction, resulting in a cumulative stress difference of approximately 29 MPa. The smaller net stress difference in the hybrid structure indicates a weaker imbalance between the opposite bending contributions of zones A and D. Consequently, the reverse S-shaped deformation associated with the cooling-induced stress asymmetry partially compensates for the positive spring-back tendency, resulting in a smaller net spring-back angle than that of the monolithic aluminum component.

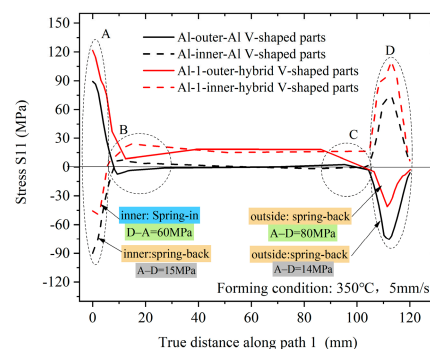


Figure 15. Comparison of stress between the aluminum alloy layers (Al-1) in Al/CF/PEEK hybrid V-shaped parts and the Al V-shaped parts (Al) before spring-back.

As discussed in Sections 3.1–3.3, the aluminum alloy layer promotes cooperative deformation with the CF/PEEK layers by constraining material flow and reducing fiber-direction shear deformation during thermoforming. During cooling, the differences in coefficients of thermal expansion, elastic modulus, and crystallization-induced shrinkage between the aluminum alloy and CF/PEEK layers result in different free contraction tendencies. Because the two layers remain mechanically coupled during cooling, this mismatch in free contraction results in mutual constraint and stress redistribution, leading to a reverse S-shaped residual stress distribution. The resulting residual stress state partially offsets the positive spring-back tendency and reduces the spring-back of the hybrid V-shaped parts.

4. Conclusions

This study numerically investigated the thermoforming and spring-back behavior of monolithic aluminum, single-material CF/PEEK, and Al/CF/PEEK hybrid V-shaped components. The cooperative deformation behavior between the aluminum and CF/PEEK

layers and its influence on wrinkling and spring-back were clarified. The following conclusions were obtained:

(1) The aluminum alloy constitutive model accurately reproduces the thermoforming and spring-back behavior of monolithic aluminum V-shaped components, providing a reliable baseline for analyzing the cooperative deformation of hybrid laminates.

(2) During hot stamping of Al/CF/PEEK hybrid V-shaped components, the hybrid materials exhibit S-shaped deformation. The aluminum alloy layer plays a dominant role in the deformation behavior of the hybrid materials, restricting the bending deformation and fiber-direction shear deformation of CF/PEEK prepreg layers. This promotes coordinated deformation between the prepreg layers and the aluminum alloy layer, thereby reducing the bending amplitude and fiber-direction shear deformation of CF/PEEK and improving deformation compatibility between the two constituent materials.

(3) During cooling, the differences in thermal expansion behavior, elastic stiffness, and crystallization-induced shrinkage between the aluminum alloy and CF/PEEK layers result in different free contraction tendencies, leading to mutual constraint and stress redistribution. This process induces a reverse S-shaped residual stress distribution, which partially offsets the positive spring-back tendency and significantly reduces the spring-back of the hybrid V-shaped components.

Author Contributions: Conceptualization, Y.L. (Yan Lu); methodology, Y.L. (Yan Lu); software, Y.L. (Yong Luo); validation, Y.L. (Yan Lu); formal analysis, Y.L. (Yan Lu); investigation, Y.L. (Yan Lu) and S.Z.; resources, Y.L. (Yong Luo), J.X., K.Z. and Y.L. (Yibo Li); data curation, Y.L. (Yan Lu); writing—original draft preparation, Y.L. (Yan Lu); writing—review and editing, Y.L. (Yan Lu); visualization, Y.L. (Yibo Li) and Y.Z.; supervision, Y.L. (Yan Lu) and Y.L. (Yibo Li); project administration, Y.L. (Yibo Li); funding acquisition, Y.L. (Yong Luo), J.X., K.Z. and Y.L. (Yibo Li). All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (Grant No. U21A20132), the Guizhou Provincial Science and Technology Program—Talent Innovation Team Project (QKH-CXTD [2025] 027), the Guizhou Provincial Academician Innovation Team Workstation for Disaster Prevention and Control through Remote Sensing (Qian Kehe Platform KXJZ [2024] 006), and the Guizhou Provincial Science and Technology Plan Project (Qian Ke He Ji Chu QN [2026] 023-1).

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The authors also acknowledge the use of ChatGPT (GPT-5.6 Luna; OpenAI, San Francisco, CA, USA) in the preparation of this manuscript. The AI tool was used for English grammar correction and language refinement, with all outputs reviewed and validated by the authors to ensure accuracy and integrity.

Conflicts of Interest: Author Yong Zhang was employed by the company China National Heavy Machinery Research Institute Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

CFRTP	Carbon fiber-reinforced thermoplastic composites
FMLs	Fiber-metal hybrid laminates
EVs	Electric vehicles
Al	Aluminum alloy

References

- Hussai, M.; Zaki, W.; Umer, R. Flexural Performance of Shape Memory Alloy/CF-PEKK Fiber Metal Laminates for Aircraft Morphing under Varied Temperature Conditions. *Sci. Rep.* **2025**, *15*, 14093. [\[CrossRef\]](#)
- Sun, C.; Dai, M.; Ying, L.; Du, K.; Chen, Z.; Hu, P. Experimental and Numerical Simulation on Formability and Failure Behavior of Thermoplastic Carbon Fiber/Al Composite Laminates. In *Numerical Methods in Industrial Forming Processes—NUMIFORM 2023*; Lecture Notes in Mechanical Engineering; Springer: Cham, Switzerland, 2023; pp. 383–393. [\[CrossRef\]](#)
- Zou, H.; Chen, Y.; Zhang, X.; Ning, C.; Pan, R.; Yang, Y.; Zhang, J.; Du, B. Enhancing the Mechanical Properties of Fiber Metal Laminate by Surface Treatment. *Polym. Compos.* **2023**, *44*, 2080–2092. [\[CrossRef\]](#)
- Sang, L.; Xing, J.; Lv, J.; Gao, S.; Hou, W. Investigation of Structure-Flexural Response Relations in Thermoplastic Carbon/Glass Fiber-Metal Laminates. *Polym. Compos.* **2024**, *45*, 5619–5632. [\[CrossRef\]](#)
- Çobanoğlu, M.; Ecmel, R.; Unlu, B.; Öz, Y.; Toros, S.; Öztürk, F. Investigation of Thermoforming Processes of Aerostructures: Simulation and Microstructural Analysis. *Int. J. Adv. Manuf. Technol.* **2024**, *132*, 5039–5052. [\[CrossRef\]](#)
- Shaikh, S.; Taufique, M.; Balusu, K.; Kulkarni, S.; Hale, F.; Oleson, J.; Devanathan, R.; Soulam, A. Finite Element Analysis and Machine Learning Guided Design of Carbon Fiber Organosheet-Based Battery Enclosures for Crashworthiness. *Appl. Compos. Mater.* **2024**, *31*, 1475–1493. [\[CrossRef\]](#)
- Grubenmann, M. Hybrid Thermoforming of Body in White Parts. Ph.D. Thesis, ETH Zurich, Zurich, Switzerland, 2020. [\[CrossRef\]](#)
- Werner, H.; Poppe, C.; Henning, F.; Kärger, L. Material Modeling in Forming Simulation of Three-Dimensional Fiber-Metal Laminates—A Parametric Study. *Procedia Manuf.* **2020**, *47*, 154–161. [\[CrossRef\]](#)
- Lu, Y.; Li, Y.; Yue, Q.; Liu, J.; Zhang, Y.; Dong, L. A Rate-Temperature-Dependent Visco-Hyperelastic Constitutive Model for UD CF/PEEK Prepregs during a One-Step Hot Stamping Forming Process. *Int. J. Appl. Mech.* **2023**, *2450007*, 1–29. [\[CrossRef\]](#)
- Lu, X.; Wei, J.; Zhao, W.; Zhang, W.; Zhou, H.; Liu, Z.; Peng, X.; Huang, Z.; Zhou, H. Model Prediction of Unidirectional Fiber-Reinforced Composites under Finite Deformation. *J. Reinf. Plast. Compos.* **2025**, *44*, 1963–1978. [\[CrossRef\]](#)
- Fischer, T.; Grubenmann, M.; Harhash, M.; Hua, W.; Heingärtner, J.; Hora, P.; Palkowski, H.; Ziegmann, G. Experimental and Numerical Investigations on the Quasi-Static Structural Properties of Fibre Metal Laminates Processed by Thermoforming. *Compos. Struct.* **2021**, *258*, 1–13. [\[CrossRef\]](#)
- Yan, D.; Li, Y.; Zhou, W.; Qian, Z.; Wang, L. A One-Step Integrated Forming and Curing Process for Smart Thin-Walled Fiber Metal Laminate Structures with Self-Sensing Functions. *J. Mater. Process. Technol.* **2025**, *335*, 1–13. [\[CrossRef\]](#)
- Blala, H.; Lang, L.; Li, L.; Alexandrov, S. Deep Drawing of Fiber Metal Laminates Using an Innovative Material Design and Manufacturing Process. *Compos. Commun.* **2021**, *23*, 1–5. [\[CrossRef\]](#)
- Li, L.; Lang, L.; Hamza, B.; Zhang, Q. Effect of Hydroforming Process on the Formability of Fiber Metal Laminates Using Semi-Cured Preparation. *Int. J. Adv. Manuf. Technol.* **2020**, *107*, 3909–3920. [\[CrossRef\]](#)
- Heggemann, T.; Homberg, W.; Sapli, H. Combined Curing and Forming of Fiber Metal Laminates. *Procedia Manuf.* **2020**, *47*, 36–42. [\[CrossRef\]](#)
- Guo, Y.; Zhai, C.; Li, F.; Zhu, X.; Xu, F.; Wu, X. Formability, Defects and Strengthening Effect of Steel/CFRP Structures Fabricated by Using the Differential Temperature Forming Process. *Compos. Struct.* **2019**, *216*, 32–38. [\[CrossRef\]](#)
- Blala, H.; Lang, L.; Khan, S.; Alexandrov, S. Experimental and Numerical Investigation of Fiber Metal Laminate Forming Behavior Using a Variable Blank Holder Force. *Prod. Eng.* **2020**, *14*, 509–522. [\[CrossRef\]](#)
- Wollmann, T.; Hahn, M.; Wiedemann, S.; Zeiser, A.; Jaschinski, J.; Modler, N.; Khalifa, N.; Meißner, F.; Paul, C. Thermoplastic Fibre Metal Laminates: Stiffness Properties and Forming Behaviour by Means of Deep Drawing. *Arch. Civ. Mech. Eng.* **2018**, *18*, 442–450. [\[CrossRef\]](#)
- Zhai, C. *Investigation on the Bending Forming and Springback Behavior of Steel/CFRP Laminates*; Jiangsu University: Zhenjiang, China, 2019.
- Lu, Y.; Li, Y.; Liu, J.; Zhang, Y.; Huang, M. Spring-back of Al/CF/PEEK Parts During One-Step Hot Stamping Forming Using a CAE Chain Considering All Process Steps. *Polym. Compos.* **2024**, *45*, 9859–9876. [\[CrossRef\]](#)
- Hahn, M.; Ben Khalifa, N.; Weddeling, C.; Shabaninejad, A. Springback Behavior of Carbon-Fiber-Reinforced Plastic Laminates With Metal Cover Layers in V-Die Bending. *J. Manuf. Sci. Eng. Trans. ASME* **2016**, *138*, 1–8. [\[CrossRef\]](#)
- Merzkirch, M.; Juin, E.; Eman, J.; Pettersson, J.; Juntikka, M.; Ahlqvist, F.; Safvenberg, O. Hybrid Manufacturing of a 3D-Shaped Fiber Metal Laminate. *J. Manuf. Process.* **2025**, *145*, 85–98. [\[CrossRef\]](#)
- Zhu, X. *Experimental Investigation on Combined Hot Drawing Process of Steel/CFRP Laminated Materials*; Jiangsu University: Zhenjiang, China, 2016.
- Lu, Y.; Li, Y.; Zhang, Y.; Dong, L. Manufacture of Al/CF/PEEK Curved Beams by Hot Stamping Forming Process. *Mater. Manuf. Process.* **2022**, *37*, 1597–1609. [\[CrossRef\]](#)
- Lu, Y.; Liu, J.; Yue, Q.; Dong, L.; Zhang, Y.; Li, Y. Effects of Ply Orientation and Processing Parameters on Spring-back Behavior in Al/CF/PEEK Hybrid V-shaped Components. *J. Manuf. Process.* **2026**, *171*, 427–447. [\[CrossRef\]](#)

26. Dörr, D.; Joppich, T.; Kugele, D.; Henning, F.; Kärger, L. A Coupled Thermomechanical Approach for Finite Element Forming Simulation of Continuously Fiber-Reinforced Semi-Crystalline Thermoplastics. *Compos. Part A Appl. Sci. Manuf.* **2019**, *125*, 1–16. [[CrossRef](#)]
27. Mo, Z. A Method for the Non-Isothermal Crystallization Kinetics of Polymers. *Acta Polym. Sin.* **2008**, *8*, 656–661. [[CrossRef](#)]
28. Lu, Y.; Liu, J.; Yue, Q.; Dong, L.; Zhang, Y.; Li, Y. Effect of Layup and Specimen Size on Spring-back and Strength in Al/CF/PEEK Hybrid V-Parts. *Polym. Compos.* **2025**, *47*, 7580–7598. [[CrossRef](#)]
29. Hsiao, S.; Kikuchi, N. Numerical Analysis and Optimal Design of Composite Thermoforming Process. *Comput. Methods Appl. Mech. Eng.* **1999**, *177*, 1–34. [[CrossRef](#)]
30. Jiao, Z.; Wang, Y.; Li, H.; Du, L.; Mu, Y.; Zheng, J.; Li, Y. Wrinkling prediction and controlling for the hot stamping of plain weave CF/PEEK prepreg in the molten state. *Compos. Struct.* **2026**, *376*, 119817. [[CrossRef](#)]
31. Sharma, P.; Gautam, V.; Agarwal, A. Effect of Punch Profile Radius and Sheet Setting on Springback in V-bending of A 2-ply Sheet. *Adv. Mater. Process. Technol.* **2023**, *9*, 416–424. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.