Research Article

Experimental study of the effect of temperature and velocity in channel forming of polyvinyl chloride composite reinforced by 3D-fiberglass with an aluminum middle layer

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Abstract
In this paper, the stamp forming process of a U-shaped cross-section channel with sharp corners of composite laminates including aluminum sheet and polyvinyl chloride (PVC) reinforced with 3D-fiberglass was investigated. The laminates were produced by manual layup and arrangement of fibers with different angles of [0°/90°] and [±45°] degrees using hot press. The process of forming composite samples was carried out at temperatures of 25, 80, 120, 160°C and different velocities of punch. The effect of parameters including layup configuration, temperature, and forming speed on the spring-back of the formed laminates and the required forming force were evaluated. The results showed that as the forming temperature increased, the forming force decreased sharply. The lowest forming force was obtained for the laminate with [±45°, Al, ±45°] layout at 160°C temperature which was equal to 0.7KN. Also, with the increase in temperature, the spring-back angle has been reduced, the lowest of which is obtained with the laminate with $[0°/90°]_3$ layout equal to 8 degrees. Finally, it was concluded that increasing the speed of the forming process results in a decrease in the spring-back angle and this effect is more pronounced at higher temperatures.

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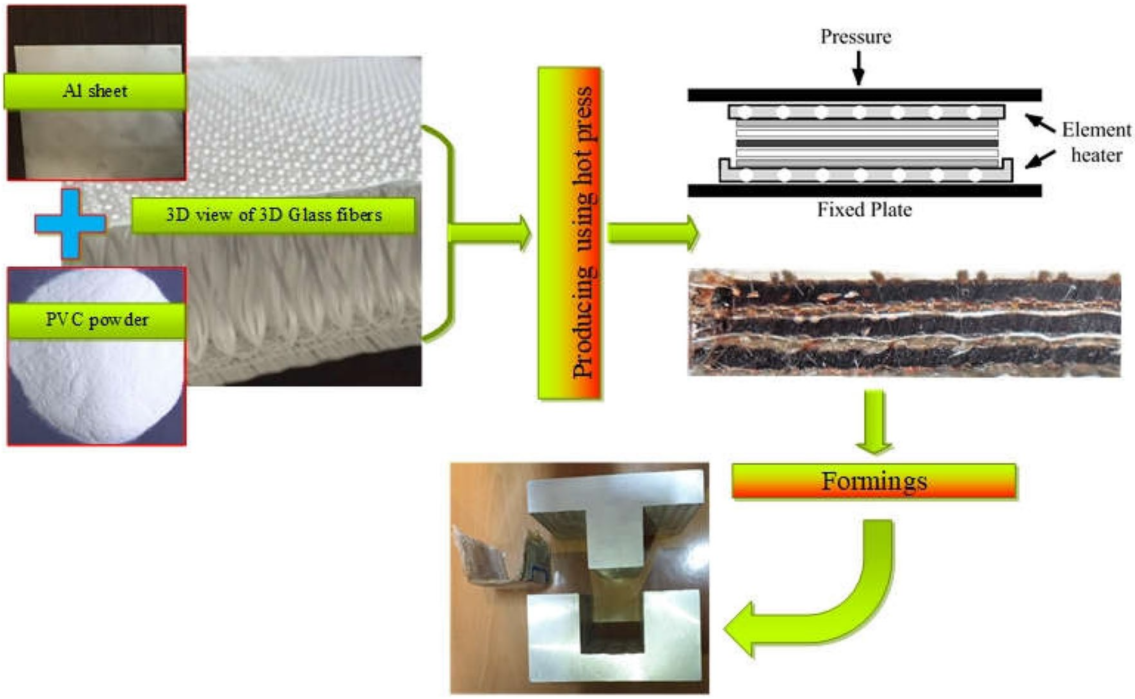
Graphical abstract



Keywords Polyvinyl chloride (PVC) · 3D-fiberglass · Fiber-metal laminate · Forming

1 Introduction

Polymer-based composites are one of the most widely used composites because of their low specific weight and good strength [1]. In polymeric composites, the base phase is mainly thermoplastic or thermoset polymers, and for the reinforcing phase, very strong fibers such as glass and carbon fibers are used. Thermoplastic composites due to their good environmental resistance, the ability to form after manufacturing, high fracture toughness, good impact resistance, recyclability, and high shelf life, are more favored by different industries than thermoset composites [2–4]. The first idea related to using metal layers in the industry was observed in the investigations and researches of the faculty of the aerospace engineering department in the Delf University of Technology(DUT) in 1978 year [5]. The existence of a metal layer with high durability against impact in the composite layers due to the interaction effects between these layers leads to more absorbing energy in the FMLs compared to composite materials without any metal layer [6, 7]. FMLs are hybrid materials composed of various layers, including metals such as Al, Mg, Ti, steel as well as polymeric layers reinforced with various fibers. FMLs are used as a substitute for metals because of their light structure, good impact, fatigue, and high weight resistance [8, 9]. In these materials, the layers are bonded by a material that if cracked in one layer, its growth stops at the next layer, and the overall crack growth rate in FMLs decreases, resulting in longer fatigue life of these materials [6, 10]. Due to its good properties, the use of FMLs in the aerospace industry has been considered [7]. In this regard, the application of GLARE in the aviation industry can be mentioned [11]. Other FMLs types that have been introduced include ARALL [12] and CARALL [13]. Although the price of FMLs is higher than common metals, the main benefit of using FMLs in the industry is reducing the weight of the structures, for example, the weight of a plane that is produced by FMLs at least decreased by 20% compared to the plane with Al sheets [12]. Metal sheets have usually good ductility, but the ductility of reinforcing fibers is low. Fracture strain of carbon fiber is up to 1% and for glass fiber is maximum 5% [14]. Plastic deformation along FMLs fibers can lead to fiber breakage, therefore, in order to shape the material, the interlayer slip has to occur. To occur this deformation mechanism to, increasing the temperature and softening of the composite layers are used. The second mechanism of deformation in the composite layers is the interlayer shearing that occurs by rotating the fibers relative to each other [15]. In the manufacture of FMLs, thermoplastics are usually used as a base material, which increases their impact resistance [16]. In addition, the thermoplastic base reduces the production cycle and increases the recyclability of these materials [17]. The mechanical properties of FMLs with a thermoplastic base have been investigated by various researchers [18–20]. Other features of this type of material are the possibility of forming them after the end of the manufacturing process [21]. Mosse et al. [22] investigated the effect of process parameters on the geometrical accuracy and delamination of polypropylene (PP) based FMLs in the stamp forming process and showed that as the forming speed increases, the geometrical error decreases. In another study [23], the authors studied the deformation of these laminates by simulating their components. Gresham et al. [24] investigated the deep drawing of FMLs with PP base and showed that with increasing process temperature, the fracture of the laminates decreases but the probability of wrinkling increases. Sexton et al. [25] investigated the deformation and strain distribution in the PP based FMLs in deep drawing process by using a spherical punch. Kalyanasundaram et al. [26] showed that the use of high temperature in the forming process of FMLs with the thermoplastic base, melts the base material and in the deformation process, the layers slip over each other. DharMalingam et al. [27], using finite element simulations, showed that the optimum temperature for achieving the highest FMLs formability with PP base is 130˚C. Valizadeh et al. [28].conducted an experimental investigation on L-die bending of UNS C10100 copper/aluminum 1100 two layers' sheet. They investigated various parameters of spring back such as, radius and clearance of die. The results showed that reduction of the die clearance and radius led to decrease of spring-back. Etemadi et al. [29] Produced layer composites involve ceramic powder and metallic layers by accumulative press bonding method. Al/Cu and Al/Cu/Al2O3 layer composites were produced in five cycles, and their spring-back, mechanical properties and plastic instability were investigated. The results showed that, the more accumulative press bonding cycles, the better particle distribution and mechanical properties were achieved. Although the tensile strength and microhardness improved in all accumulative press bonding cycles, the elongation decreased. Since the composite with reinforcement powder has higher young's modulus, they had lower spring-back values. Kazemi et al. [30] did an experimentally and numerically investigation on the forming of the AA5754/polyethylene/AA5754 sandwich composites. The experimental and numerical results were validated with each other and after that, the effect of variation in thickness of the core layer and skin layers was examined numerically. Also, the fracture analysis was carried out by SEM images.

The main aim of the manuscript is about the experimental investigation of polymer composite sheets' formation at different temperatures that were produced by 3D-fiberglass with an Al sheet in the middle by the hot press method. There are some novelties regarding this manuscript that one of the using PVC powders to fill the 3D-fiberglass to produce a composite so that, the formation of composite laminates made of reinforced thermoplastics has not been investigated with 3D-fiberglass yet. The PVC powders were added to avoid the creation of any voids and also, better impregnation of fibers and base material, the inside fiber grooves. Another novelty is that; a PVC thin film was used to better bonding. To reach the highest formability and the least defects in the composite layers during formation operation, the PVC-filled fibers layers were applied to the composite at different angles and arrangements, and their deformation mechanisms have been investigated that they have not been done yet. On the produced specimens, the channel cross-section perforation process was performed and the ductility behavior

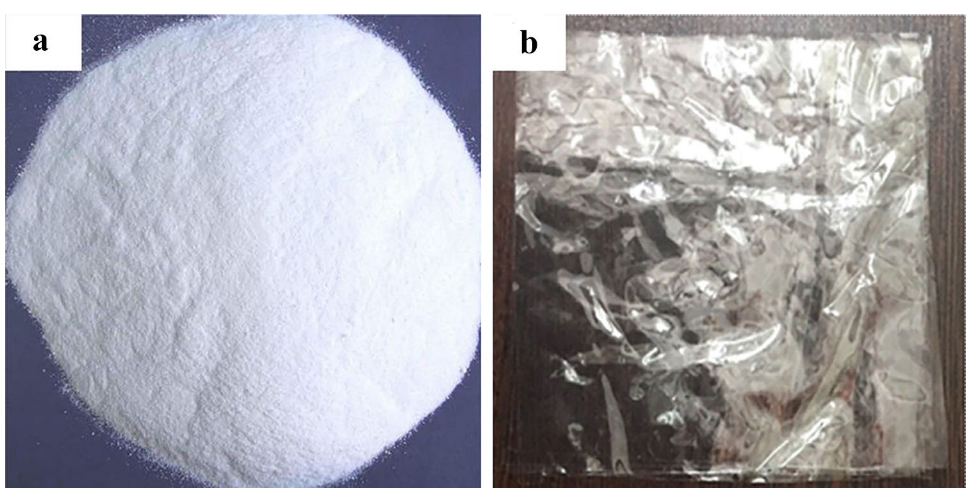


Fig. 1 **a** PVC powder **b** PVC film

and the spring-back value of their channel wall were calculated. The strength of the composite against impact forces can be increased due to the special figure of 3D-fiberglass, that involve two textile compromising with vertical joints between them [31]. Furthermore, the effect of die velocity and operation temperature were analyzed on the composite formation behavior. Finally, the composite and fibers' behavior was verified by SEM imaging.

2 Materials and composite sample production

For the production of composite laminates, film-shaped commercial thermoplastic polymer PVC with a thickness of 0.2 mm structure was used. Also, for filling 3D-fiberglass grooves, white and moisture-free PVC powders with S6558 grade was used. The sample of used powder and PVC film are shown in Fig. 1. The used 3D fiberglass was provided by Parabeam company and also, the PVC powders and PVC film were produced by Arya Sasol petrochemical company.

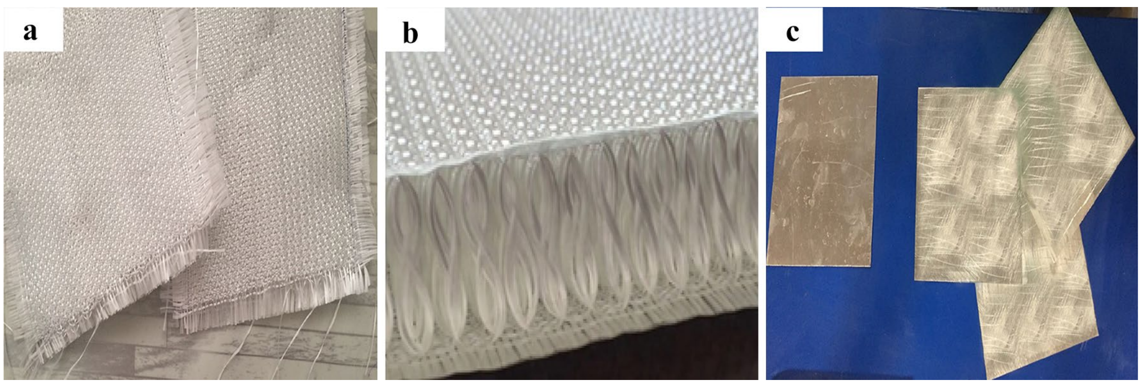


Fig. 2 **a** 2D view of 3D-fiberglass **b** 3D view of 3D Glass fibers **c** scratched Al sheet

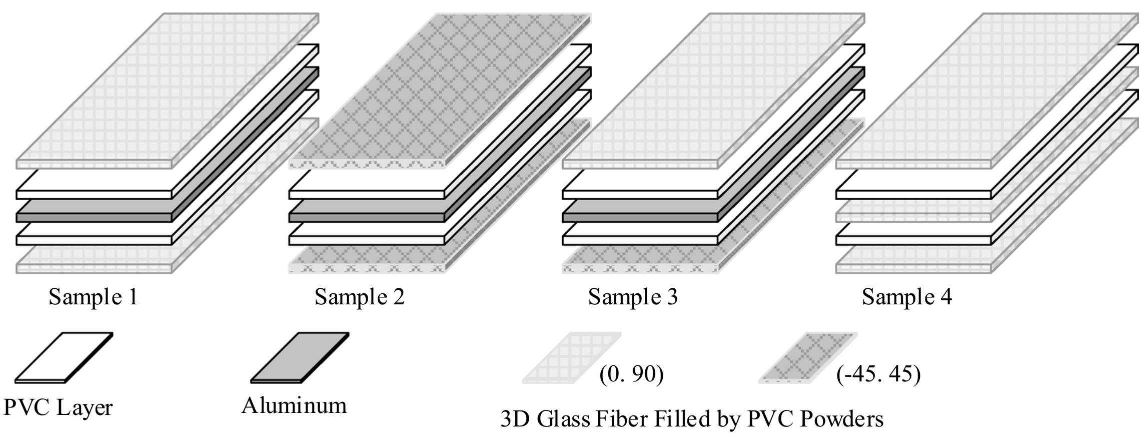


Fig. 3 The schematic parts and samples' layout

Table 1 The samples' layout

Name	First layer	Seccond layer	Third layar	Fourth layer	Fifth layer
Sample 1	3D-fiberglass [0°/90°]	PVC film	Al Layer	PVC film	3D-fiberglass [0°/90°]
Sample 2	3D-fiberglass [± 45°]	PVC film	Al Layer	PVC film	3D-fiberglass [± 45°]
Sample 3	3D-fiberglass [± 45°]	PVC film	Al Layer	PVC film	3D-fiberglass [0°/90°]
Sample 4	3D-fiberglass [0°/90°]	PVC film	3D-fiberglass [0°/90°]	PVC film	3D-fiberglass [0°/90°]

The used 3D-fiberglass for manufacturing of composite laminates are glass-textile fibers type, which is woven into two planes and joined by fibers. These fibers have 3 mm thickness and 720gr/m^3 density. The used aluminum is Al 3003 series, sheet-shaped, with a thickness of 0.5 mm and with a tensile strength of 195 MPa. As one of the most important factors for increasing strength is proper bonding between the composite layers and the metal sheet, surface treatment has also been performed on the metal sheet [32]. Since the metal surface condition plays a vital role in the quality of the composite laminate samples, to better adhesion between composite layers, a mechanical procedure was applied on the Al sheet. Firstly, the Al sheet was cleaned with acetone solution to remove any dirt, oil, or grease, and then some abrasion with low depth and irregular patterns were created by wire brush and fine grindstone. Finally, the Al sheets were again washed with acetone solution. In Fig. 2, the image of the used 3D-fiberglass and Al sheet are visible. 3D fiberglass is produced by horizontal glass fibers that are knitted in other glass fibers in the vertical direction.

As mentioned, different parameters including 3D-fiberglass and Al sheet's layout and orientations were used in the production of composite laminates. The schematic layout of the layers for the production of composite laminates and their naming can be seen in Fig. 3 and Table 1. After scratching the Al sheet surface and drying the materials, the following steps were performed to fabricate the samples.

1. Filling the internal space of 3D-fiberglass with PVC powders.
2. Assembling the layers according to the pre-designate layout.
3. Placing the layers between press plates, at 2.5 MPa pressure and 180˚C temperature for 20 min.

Laminates were heated and cooled at 8°C/min during manufacture. Increasing the temperature will melt the PVC base material and create adhesion between the layers. Finally, 3 mm thickness and 10*13 mm dimensions composite laminates were produced. To better clarify, four images were taken of filled fibers by PVC powders that can be seen in Fig. 4. A simple image of fibers, while were filling by PVC powders, was taken in which filled and unfilled fibers have been mentioned, Fig. 4a, and another image of filled fibers cross-section is shown in Fig. 4b in which fibers and PVC powders were mentioned. To verify the quality of appropriate filling of fibers, bonding, and impregnation SEM and optical microscope image were done on the

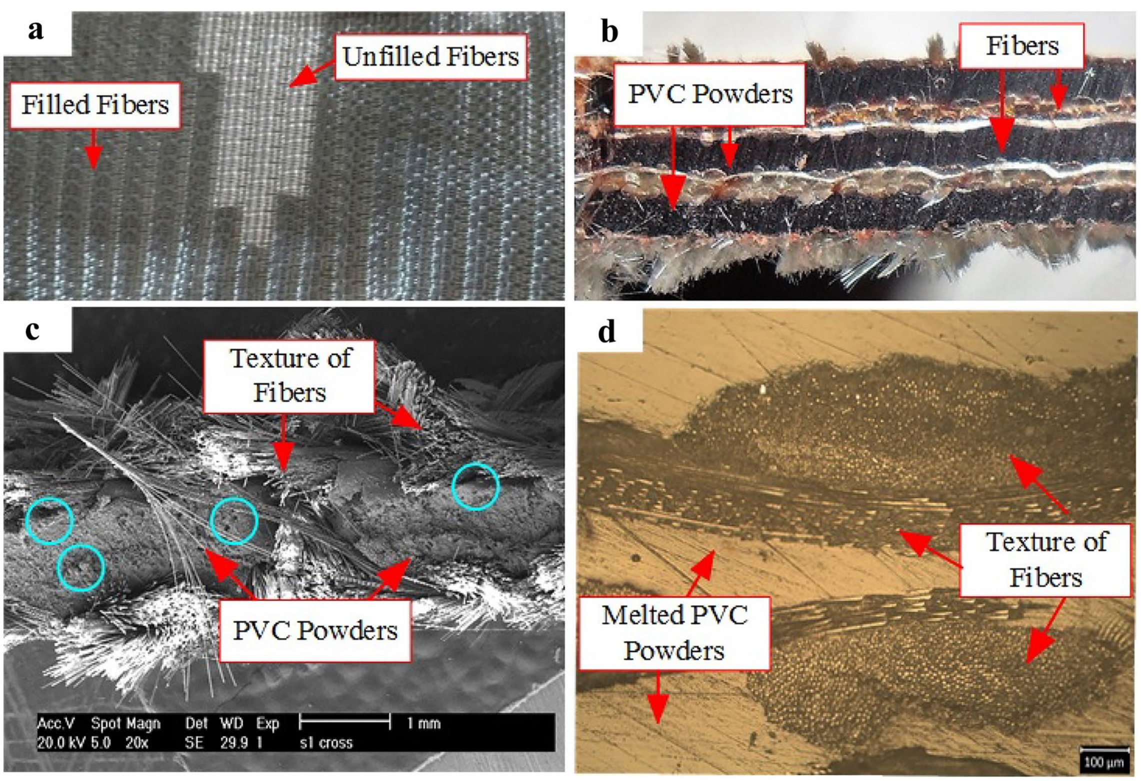


Fig. 4 **a** Image of fibers while filling by PVC powders **b** the image of laminate cross-section **c** SEM image of filled fibers **d** optical microscope image of fibers after production

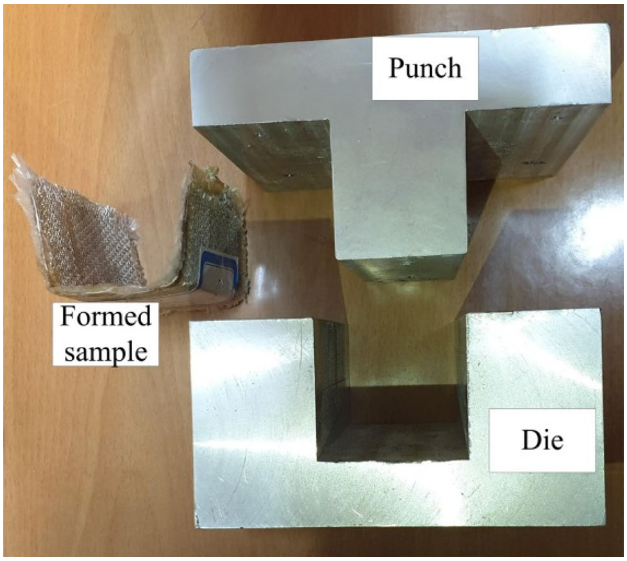


Fig. 5 The used die and the formed sample

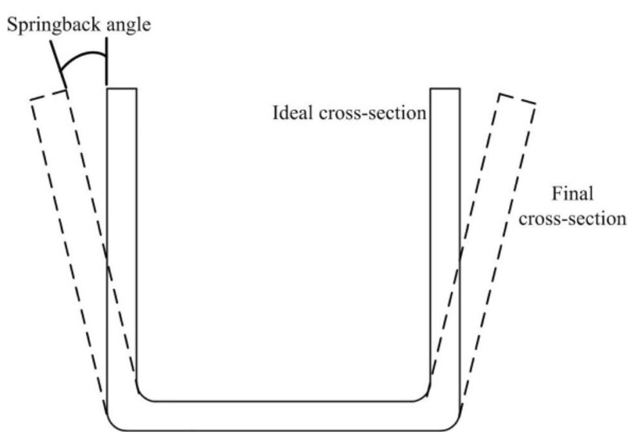


Fig. 6 The way of calculation of spring-back angle

laminates cross-section that can be seen in Fig. 4c and d, respectively. In the SEM image, the texture of fibers and PVC powders have been marked besides, some voids and porosity in the PVC powders have been shown by blue circles. Furthermore, in the optical microscope image, the melted PVC powders and fibers have been defined. It is obvious that after applying pressure and temperature, PVC powders were melted and appropriate bonding and impregnation were achieved.

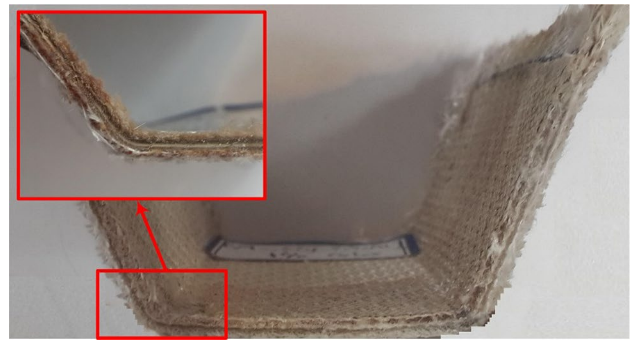


Fig. 7 Cross-section of a formed sample

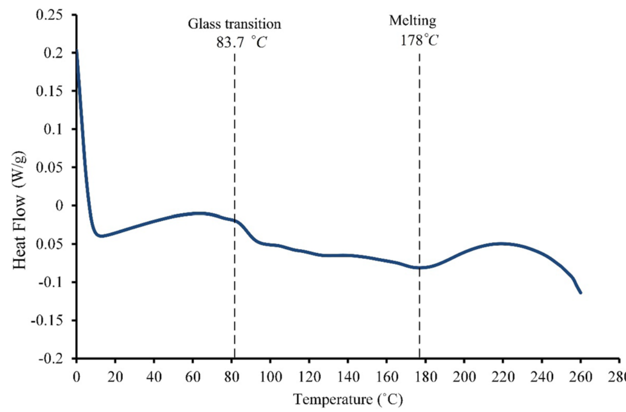


Fig. 8 The DSC diagram of PVC

3 Formation procedure and equipment

The components of the forming die and the formed sample are shown in Fig. 5. The forming process was carried out at temperatures of (25, 80, 120, 160°C) as well as punch speeds of (5, 15, 30 mm/s). To ensure for reaching the desired temperature, all the produced laminates were preheated in the furnace for 10 min and 10°C above the working temperature for the forming process. A preheating of 10°C was designed to compensate for the temperature drop caused by the sample transfer from the furnace to the die. Laminate is placed on the die and with the vertical movement of the punch by 20ton hydraulic pressing, bending, and shaping are performed. The radius of the punch and upper corner of the die was 2 mm and the inner corner angle was 90degrees. Upon completion of the process, the forming force is maintained on the sample until the sample temperature reaches to ambient temperature. After forming process and removing the sample from the die, the amount of wall-created angle on the specimens was measured and the deviation from the 90˚ angle was calculated as the spring-back angle. The calculation method of the spring-back angle is shown schematically in Fig. 6. a cross-section of one of the samples with an aluminum middle layer is shown in Fig. 7.

4 Results and discussion

4.1 Differential scanning calorimetry (DSC)

To investigate the thermal behavior of the used polymer in the process, the thermal analysis test was performed and its DSC diagram was obtained as shown in Fig. 8. According to the obtained diagram, the melting temperature of PVC is 178°C which is used in the manufacture of composite laminates. For this reason, the forming process was carried out at temperatures below 178°C to prevent the re-melting of the PVC base of the composite laminates and the uncontrolled sliding of the layers, the glass transition temperature of the PVC base was obtained 83.7°C.

4.2 Forming force

The produced laminates were subjected to a stamp forming process with a U-shaped die. The process was performed by vertical movement of the punch at a constant speed at different temperatures. The applied force to the punch increases as it progresses to its maximum value. Then, by pulling the laminate into the die, the amount of applied force to the punch is reduced. At ambient temperature for sample 3, which has fibers with a layout angle of [0˚/90˚], the fibers break suddenly along the bend and the force decreases rapidly and the maximum force is recorded lower than 80˚C. At higher temperatures, due to the softening of the base material and the sliding of the layers over one another, fibers breakdown occur less in the bending region. The maximum force on the punch during the forming process is visible in Table 2.

The results showed that for all the produced samples, the forming force decreased with increasing forming temperature. The reason for this phenomenon is the nature of the PVC-based laminates, that by applying heat softens and its strength reduces, and causes slip between layers and fibers movement through sliding in the PVC base with less force. At 25˚C which is below the glass transition temperature of the base material, due to the high shear strength of the PVC base material, the layers move harder into the die, and the forming force increases. On the other hand, the highest forming force was for composite laminates with three layers of fibers. This indicates that the adhesion between the composite layers was greater than the adhesion between the composite layers and the Al sheet. The lowest and highest forming forces were obtained at 160˚C and ambient temperatures. Also, the maximum forming force related to sample 4 at ambient temperature was 12.71KN which was 227% higher than the forming force for the same sample at 160˚C at

Table 2 The result of forming force (KN) at different temperatures and velocities

Sample	Velocity (mm/s)	25°C	80°C	120°C	160°C
Sample 1	5	7.23	5.01	4.23	1.05
	15	7.50	5.33	5.10	2.80
	25	7.55	5.86	5.74	3.92
Sample 2	5	6.00	4.23	3.17	0.70
	15	6.01	4.70	4.30	1.64
	25	6.10	4.94	4.90	3.74
Sample 3	5	6.42	4.64	4.11	0.95
	15	6.51	5.10	4.31	1.60
	25	6.54	5.35	5.05	3.90
Sample 4	5	12.71	13.07	8.47	3.88
	15	17.23	13.32	9.45	5.05
	25	17.30	13.80	10.20	6.72

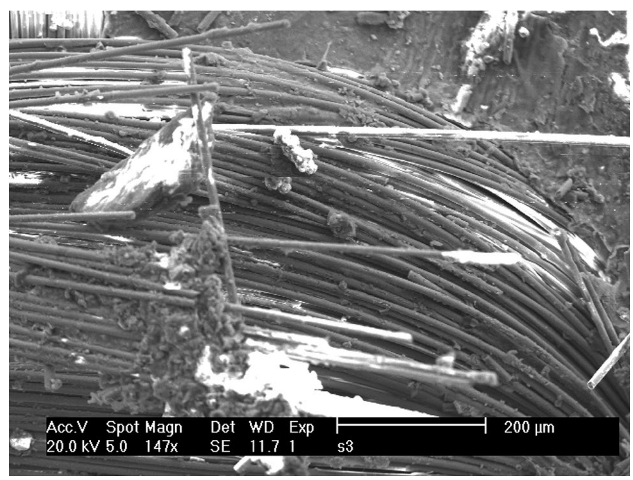


Fig. 9 The rupture of fibers in bent-area of formed sample with [0˚/90˚] at 25°C

Fig. 10 Delamination of layers in formed sample 1 at ambient temperature

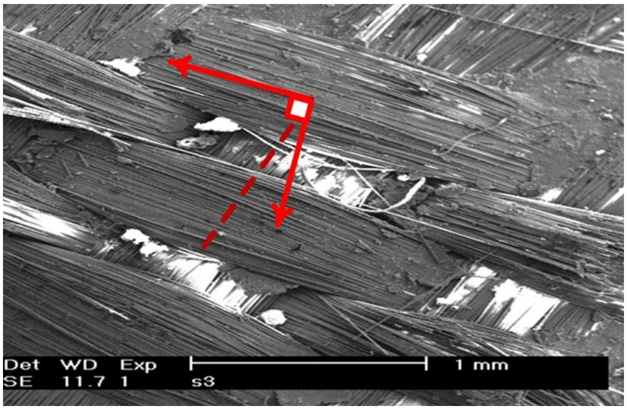


Fig. 11 The changing of fibers degree to less than 90° in the bent-area of formed sample 2 at 120°C

the lowest forming speed. In addition, the forming force for sample 3 lies in almost all cases between the forming forces required for sample 1 and sample 2.

On the other hand, the orientation of the fibers affects the forming force. The greatest strength for fibers is in their length. In the process of channel cross-section forming, in the bending area, strain and tensile stress are caused along the wall and bottom of the cross-section. For this reason, among the FMLs, the sample with two composite layers of [0°/90°] requires the greatest force for forming. Now if the forming of this sample is carried out at temperatures below the glass transition temperature, due to the higher shear strength of the PVC base and the lack of fluidity, the layers do not slip over each other, and because of the low tensile strain of the fiber, the rapture occurs in the fibers. In Fig. 9, the SEM image of the bent area of formed sample 4 at ambient temperature is illustrated which rupture of the fibers can be seen. In this case, the adhesion between the layers is good and prevents the layers from slipping over each other. And as a result, fibers that are under tension will fracture. At higher temperatures, less fracture occurs in sample 4 and this phenomenon is not observed at 120°C. Because by softening the base, its shear strength is lowered, allowing the layers to slip over each other. But in the FML sample, with [0°/90°] composite layers formed at ambient temperature, because the bond strength between the Al sheet and composite layers is low, instead of breaking the fibers under tension, the separation of the layers occurs, as shown in Fig. 10. The project results of Mosse et al. [33] revealed that increasing temperature can prevent layers' delamination during the forming process. In the case of FML consisting of two composite layers with an angle of [±45°], the mechanism of deformation changed from pure tensile to shear and the angle between the fibers changes. The interlayer shear mechanism that occurs, in this case, requires less force. As shown in Fig. 11, the SEM image of sample 2 shows the change in the angle of the fibers, with the angle between the fibers being less than 90 degrees in the bent area. However, as the temperature increases, shear between the layers also occurs, resulting in easier deformation and, as a result, less angular deformation.

The other research belongs to Martin and et al. [34] was approved that more force is needed when the forming process speed increases in the thermoplastic-based composite material. Increasing forming process speed leads to increasing deformation strain rate in the composite layers and causes more formation force is needed due to the more adhesion between interface strength of fibers and base material [35]. According to the results that have been shown in Table 2, increasing the forming speed increases the maximum required force for the forming. However, at low temperatures, this effect is very low and is mostly observed at high temperatures. At high temperatures, the PVC base softens and behaves like a liquid. Due to the viscosity of PVC at different temperatures, the amount of required stress to shear it at different speeds will also vary that as the velocity increases, the shear stress will increase and thus the forming force will also increase.

4.3 Spring-back

Unlike the semi-crystalline polymeric base material, PVC amorphous polymer exhibits relatively high elastic behavior at different forming temperatures, besides the viscous behavior. This elastic behavior causes the softened PVC base material to have an elastic strain along with the permanent strains. This results in a spring-back to the profile after the process of forming and removing forces and constraints from the formed profile. The measurements of

Table 3 The spring-back results of composite laminates at different temperatures and velocities

Sample	Velocity (mm/s)	25°C	80°C	120°C	160°C
Sample 1	5	30.2	28.7	19.3	10.5
	15	30.1	28.4	18.4	9.1
	25	30.1	28.2	17.9	8.1
Sample 2	5	38.5	31.5	28.3	11.4
	15	38.4	31	27.1	10.1
	25	38.5	30.8	26.9	9.2
Sample 3	5	35	30.2	25.9	11.2
	15	35.1	30	25.2	10.2
	25	35.2	29.5	24.1	9.4
Sample 4	5	–	27.1	14.2	9.6
	15	–	26.4	13.7	8.3
	25	–	26.2	13.1	8

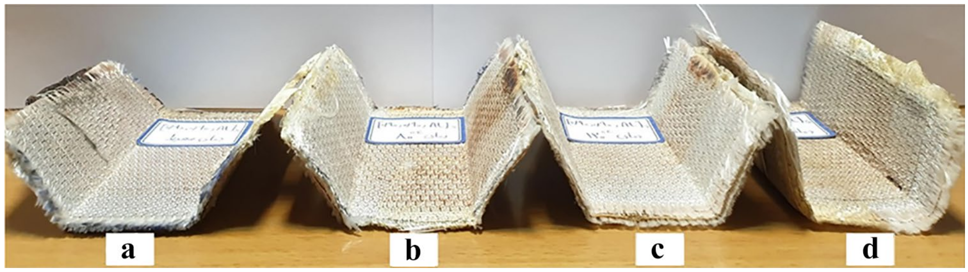


Fig. 12 The temperature effect on the spring-back amount of sample 2 at **a** 20°C **b** 80°C **c** 120°C **d** 160°C

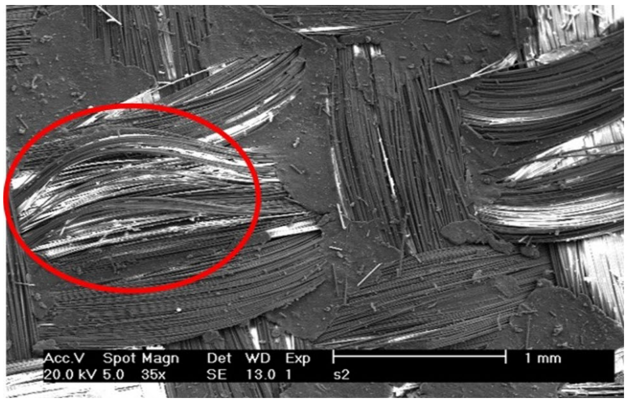


Fig. 13 The Bending of separated fibers from base material after spring-back

the spring-back angle for all samples, at different temperatures and speeds, are shown in Table 3. It should be noted that due to the failure of fibers for sample 4 at ambient temperature, no spring-back value has been reported.

The amount of spring-back of the formed laminate of sample 2 at ambient temperature up to 160°C is compared in Fig. 12. The forming temperature harms the spring-back because the higher the forming temperature, the lower the PVC elastic behavior and lower the spring-back. In fact, with increasing temperature, rather than an elastic strain on the fibers, slip between layers and inter-layer shear occurs. As can be seen, the formed composite laminates have less spring-back than the FMLs. The reason for this is the presence of an Al layer that withstands a higher elastic strain. On the other hand, this Al layer is in the middle of the FML samples and because of the low distance from the neutral axis in the bent area, it tolerates less flexural stress and produces less plastic strain.

The majority of geometrical fault in the formed cross-sections are a result of the spring-back effect that can be reduced in the U-shaped stamp forming process by increasing temperature and die velocity rate in the FMLs with polypropylene base material [22, 33]. The lowest spring-back is achieved for sample 4 at 160°C. By comparing four different samples, it is found that the maximum spring-back angle is related to sample 3 with two

Fig. 14 The formed sample 4 at 80°C temperature

composite layers with [±45°] fiber layout angles. This indicates that the deformation caused by inter-layer shearing and the change of the angle of the fibers are more elastic and easier to recover. Interlayer shearing occurs at elevated temperatures for samples with a [0°/90°] layout angle, after the sample is cooled, the layers are again stuck together and the spring-back is reduced. However, if the interlayer slip deformation mechanism is dominant, a local separation between the fibers and the base material will occur, which will lead to a more spring-back after the force is removed. In this case, the fibers that are separated from the base material are bent after the spring-back and are separated from the base (Fig. 13). The highest spring-back angles at all temperatures and velocities, after sample 2, correspond to sample 3, which has a composite layer with [±45°] fiber layouts. In sample 4, which has the least spring-back, due to the tensile state of the fibers and the residual tensile stress, the cross-section wall is curved outward. The curvature of the sample 4 wall formed at 80°C is shown in Fig. 14. This defect is less pronounced with increasing temperature and shear between layers.

According to the results, the spring-back amount decreased with increasing forming speed. The effect of forming speed on the spring-back is increased at high temperatures. At low temperatures, the PVC base material is hyperelastic and the rate of deformation does not have much effect on its properties. As the temperature increases and the viscosity decreases, the behavior of the base material changes, and the velocity increases, resulting in larger deformations and less spring-back. Due to the viscosity of the base at temperatures above the glass transition temperature (83.7°C), it can be expected that with increasing in forming speed and deformation results, the created shear stress in PVC is increased and therefore higher shear strain is created which reduces the spring-back.

5 Conclusion

In this study, polymer-based composite laminates reinforced with 3D-fiberglass filled with PVC powders and Al sheet at 170°C and 2.5 MPa pressure and 20 min were produced. The process of stamp forming the U-shaped cross-section was performed on the samples at different temperatures and forming speeds and the following results were obtained.

1. The required maximum force for forming process among the composite laminates with aluminum middle layer was related to the sample with [0°/90°, Al, 0°/90°] layout, and the least forming force was related to the sample with [± 45°, Al, ± 45°] layout. Among composite laminates with aluminum middle layer and composite laminate without aluminum layer, $[0°/90°]_3$ composite has the highest forming force, which was broken at ambient temperature after withstanding the maximum forming force. Results showed that by increasing the forming temperature, the forming force decreased and at 160°C the lowest forming force was obtained.
2. The Spring-back of fibers is one of the most important defects in the formation of PVC-based composites, which decreases with increasing temperature. The highest spring angle was related to the specimen with [± 45°, Al, ± 45°] layout and the lowest one was $[0°/90°]_3$ composite laminate which at 160°C temperature and maximum forming speed has 8 degrees of spring-back. Also, after 80°C, the spring-back angle decreased significantly.
3. The delamination between layers was seen only at [0°/90°, Al, 0°/90°] layout; this fault occurred at all forming temperatures. The failure occurred only in $[0°/90°]_3$ composite at ambient temperature. Wrinkles and rupture of fibers were observed only in these composite specimens.
4. By increasing the velocity of the forming punch, and due to the viscous behavior of the base material above the glass transition temperature, the forming force has increased. On the other hand, the amount of spring-back has been reduced so that the lowest spring-back among all processes occurred at above ambient temperature and the speed of 25 mm/s.

Data availability The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study. These authors are currently working on the effect of other parameters on the forming process.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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