Two Dimensional (2D) P-Aramid Dry Multi-Layered Woven Fabrics Deformational Behaviour for Technical Applications

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Abstract. In today's scenario for the various technical applications, from composites to body armour, the material mouldability along with its mechanical property become very important. In the present study, two dimensional (2D) woven fabrics made of para-aramid high performance fibres in multi-layer dry structure were used for investigating different forming characteristics. The different layers were arranged with 0°/90° orientation for deep drawing formability test to analyse the effect of number of layers and blank-holder pressure (BHP) during the test. Specific preforming device with low speed forming process and predefined hemispherical shape of punch has been applied. Using fine photographic analysis, some important 2D multi-layer fabrics forming characteristics i.e., material drawing-in, surface shear angle etc. from the imposed deformation have been observed, measured and analysed for better understanding and comparison. The result revealed that the mouldability behaviour of the multi-layered dry textile fabric preforms is directional, and closely dependent on blank-holding pressure and number of layers. This indicates both parameters should be carefully considered while material deformation to avoid the formation of wrinkling and maintain other mechanical properties on final application.

1. Introduction
Different stacked layers of two dimensional high performance fabrics are widely used for a considerable amount of applications [1]. Besides using flat 2D fabrics especially for conventional products like apparels, some technical applications such as protective clothing, i.e. military helmet, female body armour, and textile reinforcement and composite for aeronautical, naval and automotive applications need to mould the fabric into 3D shapes. In order to achieve this particular 3D shapes, the formability property of the specific textile material plays a great role. “Mouldability”, is generally defined as the performance of a planar textile structure to be directly deformed at macro scale by changing the angle between two yarns systems at crossover points, to fit three-dimensional components without the formation of wrinkling’s, kinks or tears [2-4]. In today’s more complicated and advanced manufacturing process, using proper mouldability, cutting of planar textile fabrics to fit three-dimensional shapes could be eliminated. This will not only increase the productivity of the material fabrication, but also enhance the mechanical properties of the specific parts due to the
maintained integrity of the material. Many researchers have tried to carry out various experimental, numerical and theoretical investigations to understand the mouldability behaviour of the material using different methods. For example, the mouldability property and its parameter analyses of different 2D [5-9] and 3D [8] textile reinforced laminated composite have been conducted and quantified by many researchers. Apart from textile reinforced laminated composite, dry multi-layer woven fabrics are also increasingly employed in the field of many technical applications. For example, in soft body armour design, different kinds of multi-layer high performance woven fabrics are stacked together with different methods to give a good ballistic protection. However, the material should have not only good mechanical performance but also flexibility. Meanwhile, only few research works have been published related to mouldability and its analysis related to dry multilayer textile structures [10]. Even the situation becomes more complex when it is required as to designed curved shapes i.e., female body armour for accommodating the bust area. In order to accommodate different curvy parts of females including the bust area [11] different methods such as traditional cut-and-sew with darts, stretch folding and fabric folding have been used so far. Developing and assembling of different parts of panels using those methods with seams and stitching could affect the ballistic performance, well-being and comfort performance of the final garment. To overcome those problems, different researchers also mention to use good mouldability material, new design process and latest technological solutions [12-15]. In general the mouldability of woven fabrics greatly depends on fabric shear rigidity, which mainly comes from abrasion between the warp and weft yarns at the cross-over points. Besides shear rigidity, significant number of study also urged different factors should be considered while mouldability processes. One of the research work [16] publicized that thick and dense multilayer fabric has a uniform surface as co MPa red to low density and thin fabric, whereas tow-aspect ratio of external layers was found greater than the tow-aspect ratio at internal layers for moulded angle interlock fabric. Another study has also designed and manufactured low shear rigid angle interlock fabrics by considering various structural parameters, i.e. warp density, weft density and weft layers in order to assess the parameters effect on their mouldability behaviour [17]. Another study [18] also tried to investigate the effects of the blank holder force (BHF) on the mouldability behaviour of non-crimp fabrics with chain stitches using varying blank holder force from 0.5 to 61.4 kgf.

The current research work is to investigate the effect of blank-holding pressure (BHP) and numbers of layers on the moulding behaviour of 2D aramid weave multi-layered panels. Using a slow process forming process, this investigation tried to observe and measure to understand various important forming parameters i.e. Force-deformation value, surface shear angles, material drawing-in etc. of the different developed sample specimens.

2. Material and Experimental Procedures

2.1. Materials

2.1.1. Sample fabrics. So far many technical products including soft body armour have been designed and developed by using high performance 2D woven fabric. For this particular research work, Twaron CT-709 2D plain weave fabric made with linear density of 930dtex and yarn density 105 yarns/10cm for both warp and weft yarns. The areal density of the fabric is 200 g/m². The properties of the fabrics are presented in Table 1.

| Fibre Type | Linear Density, Dtex | Weight, g/m² | Fabric Density Warp/10cm | Tenacity at Break, mN/tex | Strength at Break, N | Elongation at Fracture, % |
|------------|----------------------|--------------|--------------------------|--------------------------|----------------------|--------------------------|
| Aramid     | 930                  | 200          | 105 105                  | 2.35 225                 | 3.45                 |

The four different sample panels were composed of one (01), five (05), ten (10) and fifteen (15) fabric layers. Each sample panels were also prepared for testing three different blank-holder pressures.
Fabric layers were arranged one over another without using any kind of stacking methods, but griped at the edges using tapes to stabilize the layer and protect the edge from yarn frying while performing as showing in Figure 1.

2.1.2. Sample preparation. Dry multilayer panel samples made of Twaron CT-709 2D plain woven fabric were developed with 0°/90° orientation in hybrid forms as presented in Table 2.

| No. | Sample designation | Fabric type         | No. of layer used | Applied blank-holder pressure ( MPa ) |
|-----|--------------------|---------------------|-------------------|--------------------------------------|
| 1   | 2DWF-L-01          | 2D plain weave      | 01                | 0.1                                  |
|     |                    |                     |                   | 0.2                                  |
|     |                    |                     |                   | 0.3                                  |
| 2   | 2DWF-L-05          | 2D plain weave      | 05                | 0.1                                  |
|     |                    |                     |                   | 0.2                                  |
|     |                    |                     |                   | 0.3                                  |
| 3   | 2DWF-L-10          | 2D plain weave      | 10                | 0.1                                  |
|     |                    |                     |                   | 0.2                                  |
|     |                    |                     |                   | 0.3                                  |
| 4   | 2DWF-L-15          | 2D plain weave      | 15                | 0.1                                  |
|     |                    |                     |                   | 0.2                                  |
|     |                    |                     |                   | 0.3                                  |

Figure 1. (a) Model and (b) Photographic views of sample preparations for performing.

The sample fabric were cut and prepared in 240×240 mm² surface dimensions. As it is indicated also in Figure 1, the different guide lines with coloured pens, known as “tracers”, and different points “indicators” has been illustrated on warp and weft directions of the preform surface. Basically this grid structure will assist for easy follow up, measure, understand and analyse the different set of measurements and mechanical forming characteristics, i.e. material drawing-in, material deformation recovery, thickness of the fabrics in different positions, surface shear angles etc. of the perform while and after forming process.

2.1.3. Experimental equipment and procedures. Experimental equipment set up. The formability testing machine, based in GEMTEX laboratory, is used for conducting this research. The machine is a
modified pneumatic based testing machine adapted to a fast, safe and ambient temperature stamping process. The forming using a pre-defined hemispherical punch is performed on a specific formability device.

A device specifically designed to perform the forming and used to observe the formability properties while forming process of different sample is presented on Figure 2. This particular forming bench is composed of both a static blank holder system and an open die which distribute pressure provided by four jacks to the edges of the preform. A non-heating punch gives the desired shape through a vertical and controlled motion driven by a pneumatic jack. The die can be opened to access direct observation of the different characteristics during the forming process. The two most important parameters which have to be considered during forming process are the blank holder pressure and the velocity of the punch. While punching process, the sample should appropriately mount on the proper sample holding position. Moreover, the pressure applied on the blank holder must be properly set in all direction of the sample and sufficient enough to maintain the good preform. Too high or too low blank holder pressure may result sample folds and yarn breakage respectively. Meanwhile the position of the punch which is found below the holder is controlled by a position sensor and equipped with a stress sensor to measure forces applied by the punch to the performing material. Besides its motion is controlled by using a piloted four jacks mounted below the punch. This device has been also developed to adapt and preform different shape and sizes of punch and die.

Figure 2. Modified pneumatic based formability testing machine [2].

Beside direct observation, a camera, located on the top of the forming bench, also helps to observe and capture the forming behaviour of the sample during the forming process. Even though various shapes of punch are available for analysing the different forming characteristics of the material, we have preferred to use a 30 mm diameter semi hemispherical shaped punch which ensures a symmetric double curvature deformation during the forming process. This particular hemispherical shape punch has been mostly used to observe the local and global deformations of the different preformed samples by following the different path of yarns in the structure both in the warp and weft directions.

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2.1.4. Experimental Procedures. While testing, the different 2D layers of sample woven fabrics turn by turn are placed between the blank-holder and an open die. While adjusting the sample on the bottom holder, on the two sides the light will apply on the surface for finding the proper arrangements and position of the perform material. Later the four jacks, governed by pneumatically and found at the top part of the machine which will be connecting to the blank holder, will apply a sufficient adjustable pressure on the fabric. In the forming process, different important forming parameters such as material draw-in, the in-plane shear, the inter-layer sliding, help to measure the material behaviour.

![Figure 3. Some deformed shape of samples at 0.2 MPa (a) While forming, (b) After forming.](image)

Another electric jack linked to the punch imposes a movement (punch displacement) and a load sensor machine (in different units) will acquire the punch force while the forming process. In punching of the different samples of the 2D woven sample fabrics as shown in Figure 3, the initial corresponding punch displacement for all sample were 45 mm and applied pressures on the blank-holder were 0.1, 0.2 and 0.3 MPa. In Figure 4, for a given pressure of 0.2 MPa, different samples of 2D fabrics with respectively 1, 5, 10 and 15 layers have been observed during and after the forming process. In order to improve the understanding of the given sample and predict the suitable material for double-curved shape forming, the investigation of stamping behaviour of each sample will be performed by analysing the different characterizations of in-plane, out of plane and through-the-thickness of the formed samples.

3. Results and discussion

3.1. Evolution of the punching force with the stamping time

While forming process the force applied by the installed punch was governed by a load sensor of 500 N (±0.3 %) which is directly connected with the punch. The punching force has been slowly applied in the bottom to the forming material with the help of pneumatic methods. The evolution of the punching force in relation to the stamping time for the different samples in specified holding pressure by the blank holder has been recorded. The corresponding average forming force versus forming duration relationships for the different samples is illustrated in Figure 4. As it can be seen from the figures all the curves of the preform samples at the different holding pressure show more or less a similar trend
for all samples. At the beginning, the force shows an increase while deformation until it reaches the maximum displacement. Later, a constant force of punch has applied to maintain the final shape of the deformed sample. However, it is clearly shown that as the numbers of layers in the sample become more, it needs high punching force in order to achieve the maximum displacement. Moreover, it is evidently revealed that for the given sample panels, as the capacity of blank-holder pressure increases, the force required to achieve the maximum deformation for the specific number of layers has been increased. This is due to the punching force applied to reach its maximum displacement has been shared with the corresponding number of layers. Generally we can conclude that, the punching force is directly related with both the number of layers and the blank-holder pressure applied in the panels during forming.

**Figure 4.** Punching force while forming in different blank-holder pressures (BHP) for different number of sample layers.

3.2. Different forming characteristics after forming process

3.2.1. Material drawing-in measurement in weft and warp direction. The material drawing-in values are mostly expressed in terms of the consumed length of the sample fabrics both in the warp and weft directions during the forming process. Our research has used the quarter portion of the sample region for analysing and determining the material drawing-in values of the sample at different points both in warp and weft directions. This is due to the force applied by the hemispherical punch and the formability properties are nearly uniform on the divided four quarter sample regions shown in Figure 5. The sample drawing-in values were measured using ImageJ software by taking an appropriate and
precise picture at the top view of central point and perpendicular to the surface of the preform. While
taking pictures, sufficient distant from the sample has been considered in order to reduce errors due to
shooting. Figure 5 indicates the schematic diagrams of the sample material drawing-in at the different
points while deformation.

![Figure 5](image)

**Figure 5.** The schematic diagrams of material drawing-in while deformation.

![Figure 6](image)

**Figure 6.** (a) Material drawing-in values of sample (2DWF-L-05) in warp and weft direction at
different BHP (b) Material drawing-in values of different samples at various point in weft and
warp direction at 0.2 MPa BHP.

In order to investigate the effects of different BHP on sample drawing-in values, sample 2DWF-L-05 were chosen. As it can be shown from Figure 6(a), the higher blank-holder pressure, the drawing-in value of the sample to be drawn has been reduced. This is mainly when the blank-holder pressure increases, the edge of the sample will be firmly held and prevented from drawing-in. However, in order to reach to the maximum deformation, the other part of the sample region which was not held by the blank-holder will be solely responsible for the deformation. Moreover, it is also noticed that the drawing-in value of the sample has been increased from edge to centre of the sample. In general it was also observed that the material drawing-in value in the warp direction is slightly higher than in weft direction, mainly due to lower crimp value of weft yarns co MPa red to warp yarns. Moreover, an
investigation has been also carried out in order to see the number of layer effects in the sample panel drawing-in values. We have selected and applied 0.2 MPa holding pressure for all the samples and measure the values at various indicator points in both weft and warp direction.

The result is illustrated in Figure 6(b), and depicts that for the specified value of blank holding pressure (BHP), the majority drawing-in value reduces as the number of layer increases. This is due to the increase of layers; the force which was applied on the sample panel fabrics by the blank holder will be distributed to the individual samples. From the measurement, the maximum and minimum drawing-in values achieved in weft direction were 2.11 & 0.476 mm, 1.89 & 0.427 mm and 1.602 & 0.382 mm at 0.1, 0.2 and 0.3 MPa BHP respectively. Whereas in warp direction 2.2 & 0.52 mm, 1.97 & 0.448 mm and 1.803 & 0.39 mm at 0.1, 0.2 and 0.3 MPa BHP respectively. Most of the maximum and minimum drawing-in values were found at the centre (point D’ and G’) and edge corner (point A’) respectively.

3.2.2. Surface shear angle measurements of the material. During forming processes of the different materials, wrinkling is one of the most common faults which often leading to unexpected failures. This common and important parameter has always a strong relationship with the shear angle of the material. In general shear angle is the angle between the warp and weft yarns. In the deformation research work it is usually captured and optically measured with the help of camera. In our particular study, due to the hemispherical punching system, one fourth of useful zones of the deformed plies as presented in Figure 7 were used to determine the shear angle measurement. Using the marked region tracking method and with the help of the dedicated ImageJ software at the measurement precision of ±0.25°, it is possible to measure and study the in-plane surface shear angle during the whole preforming stage.

While forming, the shear angle is only calculated for areas where no wrinkling was found. In this particular research for analysing the effects of number of layers in the preform, all the prepared samples (01, 05, 10 and 15 layers) were investigated with the same blank-holder pressure (0.2 MPa ). In general, from the measured shear angle values of each region of different layer samples, the minimum shear values has been observed on the top and corner edge of the regions (region 1, 2, 29,
30, 34, 35, 36), whereas the maximum shear values was found around the diagonal direction on the neck/edge of the deformed regions (region 8, 10, 11, 12, 15, 16, 17, 18, 20, 21). Besides, along all the measurement, the maximum shear angle was found 22° in region 20, 25° at region 20, 24° at region 16 & 21 and 34° in region 16 for 2DWF-L-01, 2DWF-L-05, 2DWF-L-10 and 2DWF-L-15 respectively. Whereas the minimum shear angle value was achieved 2° in region 34, 0° at region 1, 0° at region 1 and 34 and 1° in region 34 for 2DWF-L-01, 2DWF-L-05, 2DWF-L-10 and 2DWF-L-15 respectively.

### Table 3. Measurements of surface shear angle for different samples at 0.2 MPa BHP.

| No. | Surface shear angle range | Severity | Number of marked region for specified shear angle in different sample |
|-----|---------------------------|----------|---------------------------------------------------------------|
|     |                           |          | 2DWF-L-01 | 2DWF-L-05 | 2DWF-L-10 | 2DWF-L-15 |
| 1.  | 0° - 4°                   | Extremely less | 14 | 14 | 13 | 13 |
| 2.  | 5° - 9°                   | Very Less | 15 | 8 | 7 | 8 |
| 3.  | 10° - 14°                 | Less | 3 | 7 | 6 | 9 |
| 4.  | 15° - 19°                 | Moderate | 3 | 4 | 8 | 4 |
| 5.  | 20° - 24°                 | Severe | 1 | 3 | 2 | 0 |
| 6.  | 25° - 29°                 | Very severe | 0 | 0 | 0 | 0 |
| 7.  | 30° - 34°                 | Extremely severe | 0 | 0 | 0 | 2 |
| Total |                         |          | 36 | 36 | 36 | 36 |

**Figure 8.** Surface shear angle values distributions for different number of layer samples of quarter regions at 0.2 MPa BHP.

However, in order to clearly understand the shear angle analysis of the different samples, thanks to the accuracy of the measurements, we tried to segregate the different shear angle values of the specified marked region (36 in number) into seven categories with the categories of 5° for the different samples, as recorded in Table 3.

Even though the values in the table did not reveal the shear angle of each and every region of the marked area, the analysis result shows that except some fluctuation and quite unpredicted values, in majority the relationship between the numbers of layers in the sample has a linear relation with the amount of the shear angle in the surface. As it is presented from Figure 8, the sample with small number of layer has faced less amount of surface shear angle (less severe), whereas large amount of shear angle (more severe) occurred in the high number of layer samples. Besides, in order to understand the blank-holder pressure (BHP) influences on the shear angle values, the sample with same layer number (2DWF-L-05) but different BHP (0.1 MPa, 0.2 MPa and 0.3 MPa) was considered. Figure 9 shows the effects of BHP on the given sample panels in the specified regions. The result shows clearly that the shear angle value has higher values as the blank holding pressure increase.
4. Conclusions

In the present study, different layers (01, 05, 10 and 15) of stacked 2D woven aramid fabrics were investigated for their different moulding behaviour using different blank-holder pressures (0.1, 0.2 and 0.3 MPa). The various moulding behaviour of the sample, i.e. through-the-thickness variation, material drawing-in, surface shear angle etc. were considered for the study. In general, it is noticed that formability behaviour in deformation are very important to be considered in which it will have a significant role on ultimate mechanical properties. General result shows that in preforming, both the blank holder pressure applied and number of layers in the sample have significant role on the forming properties of the samples. For instance, for all applied blank holder pressures, the drawing-in values of the different samples in the warp direction are slightly higher than in the weft direction due to the slight bending of weft yarns compared to the warp yarns. As the holding pressure of the blank holder increases, the drawing-in value has been reduced and the region which was not maintained by the holder is solely responsible for the deformation. Regarding the surface shear angle, it becomes more severe as the number of layers and pressure applied increased. The result will give a hint for different researcher, scientist, designers and manufacturer to consider blank holder pressure and number of layers used while forming in the application of technical product such as soft body armour.

5. References

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