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REVIEW

Improvements in the warp-knitting process and new patterning techniques for stitch-bonded textiles

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Stitch-bonding technology offers a highly effective process of manufacturing reinforcement textiles for composite materials. This innovative technology is based on joining layers of threads and fabric with a knitting thread to create a layered structure, a multi-ply. Thus far, the knitting thread has restricted the positioning of individual layers in the fabric. It has been impossible, until now, to position warp layers symmetrically in one step as the outer layers of the fabric. It has been accomplished as a multi-step process, which in turn compromises productivity and quality. With the needle shift technique as an extension of the stitch-bonding process, all previous restrictions on multi-plies are eliminated. Both outer warp layers can be secured in one procedure by incorporating a shift of the needle bar during the stitching process, creating endless possibilities for the arrangement and patterns in the stitch-bonding process. For the numerical description and diagramming of the new patterning techniques, we have reworked and expanded previous illustration models.

Keywords: warp knitting; stitch-bonding; patterning; chain notation; lapping diagram

Introduction and terms

Stitch-bonding is categorized as a knitting process and is in fact a special type of warp knitting. We have expanded the general term of a stitch-bonding machine beyond the common definition to all RL-flat warp-knitting machines used to bind fabrics or layers of threads (the base material) with knitting threads. With this type of machine the product generally formed consists of at least one warp-knitting system and the base material. Our definition of a stitch-bonding machine is

- a warp-knitting machine (simultaneous needle movement),
- with one flat needle bar (needles located side-by-side, right–left-machine type),
- one or two, theoretically more, warp-knitting systems/guide bars,
- which join base materials by means of the warp-knitting systems,
- independent of the form of the knitting components or the needle.

Stitch-bonding machines for non-woven fabrics function according to the same stitch-bonding principle. All needles work simultaneously; however, instead of working in a thread, they use fibers pulled from a furnished fiber web. For the purpose of this paper, these special stitch-bonding machines are not considered to be a subcategory of stitch-bonding machines. They can be viewed rather as an expanded variation of RL-flat warp-knitting machines.

Fabrics manufactured on stitch-bonding machines, termed commonly as stitch-bonded fabrics, will be referred to here as stitch-bonded multi-plies (Hausding, Franzke, & Cherif, 2007) to emphasize the fact that they consist of one or more different plies, which is significant for their properties. Stitch-bonded multi-plies are defined according to the German standard DIN 61211(2003), as

> . . . textile fabrics, produced by embedding the stitching thread in a mesh-like fashion into a flat base material.

Stitch-bonded multi-plies are coined in the prevailing literature under various names such as, multiaxial multi-ply fabrics (MMF), non-crimp fabrics (NCF) or multiaxial warp knits (MWK). However, in the opinion of the authors, these terms do not suitably define stitch-bonded multi-plies, since other textile materials could be also labeled as such.

Per definition, stitch-bonded materials are composed of one or two warp-thread systems and at least one base material. Base materials in stitch-bonding are threads, fabrics (webs, membranes etc.) or a combination of different base materials. Stitch-bonded multi-plies can be categorized under the general term multi-ply and defined as a fabric composed of one or more layers of parallel and stretched threads and/or additional material, fixated by knitting threads, where the thread layers can be positioned at different angles to one another and possess different thread densities.

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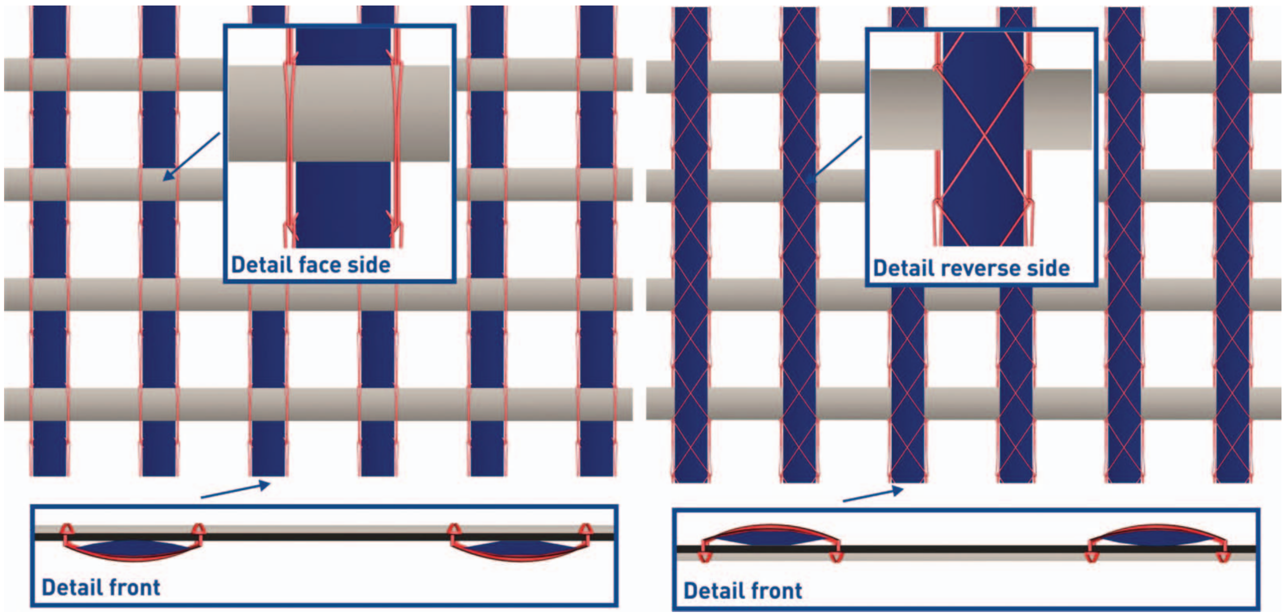

Figure 1. Biaxial stitch-bonded multi-ply; pattern double tricot.

Positioning of layers in the stitch-bonded material

Layer position restrictions in the conventional stitch-bonding process

The basic version of a stitch-bonded material is the combination of a warp-knitting thread system (i.e. in the pillar-stitch pattern) and a weft-thread layer. A warp layer alone cannot be fixed by a warp-knitting thread system. The warp thread is fixed on the reverse side of the fabric by means of a sinker loop (does not apply for the pillar stitch), but for the face side of the fabric at least one weft-thread layer is necessary (Figure 1). Therefore, with present technology, it is impossible to manufacture stitch-bonded materials where both outer layers are warp layers. Until now, it was only possible to produce such fabrics after the initial manufacture in additional steps, for example by further stitch-bonding.

This restriction poses one of the biggest disadvantages seen in stitch-bonding compared to other manufacturing methods, especially where multi-plies are implemented as semi-finished products for use in composites (Du & Ko, 1996; Dumolard & Shimell, 2007; Truong, Vettori, Lomov, & Verpoest, 2005). A symmetrical positioning of layers is possible with weft knitting, the double flat warp-knitting technique and in material-bonded fabrics. However, each of these techniques has disadvantages, which leads to the conclusion that it is profitable to modify the stitch-bonding technique to allow unrestricted layering possibilities (Hausding et al., 2007). The combination of the various positive characteristics of multi-plies, specifically the wide selection of workable fiber materials, the advantages of non-crimping threads, a broad spectrum of layering angles and the countless possibilities of materials which can be integrated in the multi-ply, lends itself to an expansion in multi-ply applications and developments. Multiple sources offer various solutions, which could render a free positioning of layers.

Alternatives in the enhancement of the stitch-bonding process

In order to combine base materials with one another by means of a loop system, it is necessary that the needle with the warp thread for the loops penetrates the materials in each work step. To attach warp layers, it is also necessary that the warp-knitting threads be led over the warp and fix the warp layers at regular intervals. This means that the warp and knitting threads must move in accordance with one another as well as perpendicular to the working direction of the stitch-bonding machine. This is possible on all stitch-bonding machines for the reverse side of the fabric. To also attach the warp threads on the other side – the face side of the fabric– there are a few alternatives:

(1) The knitting thread completes the movement,
 (a) moved by the yarn guide,
 (b) moved by the needle.
(2) The warp thread completes the movement.
(3) Attachment is completed by turning and repeating,
 (a) in a two step process,
 (b) in one step.

Principally, the attachment of the warp threads on the face side of the fabric could be completed by guide bars located on the needle side (Alternative 1a). Warp-knitting machines can perform this type of pattern if the warp threads are furnished by a third guide bar placed between the two standard guide bars (K.P. Weber & M. Weber, 2004).

However, this solution cannot be applied to stitch-bonding machines without a basic modification. It requires that the guide bars work independently of one another. Anon. (1985) developed such a solution, but without the addition of warp-thread layers. Problematic is the high complexity of such a solution and a decrease in efficiency due to the longer needle strokes and the complicated controls (Anon., 2003a).

Instead of moving the knitting thread, it is also possible to use the needle for this step (Alternative 1b). The needle is shifted sideways with the loops in the needle hooks after piercing the base material, and binds them in the next knitting cycle. In this manner, outer warp layers can be fixed (Anon., 2003a, 2003b). Stitch-bonding machines producing non-woven fabrics have been modified to better fix the fiber web using this lateral movement of the needle (Hoffmann, 1987), however, it has never become a common practice.

A lateral shifting movement of the warp threads by means of a controlled filler thread guide bar is also a possible means of attaching the layer to the face side of the multi-ply (Alternative 2). Stockmann (2002) presented such a solution; however, only for the reverse side of the fabric. Problematic is the increased tension on the warp threads caused by the lateral movement, which generally leads to damage of such, especially when using sensitive materials such as glass or carbon.

The simplest solution of joining warp layers on the outer sides of a fabric on a standard stitch-bonding machine is to complete the process in two steps (Alternative 3a). In the first step the warp threads are joined to one side of the multi-ply, and after turning the fabric, the stitching process is repeated on the other side. This process is described by Anon. (1997) where two asymmetrical multi-ply fabrics are combined with one another by means of stitch-bonding. In this manner, the warp-thread layer can be positioned anywhere within the manufactured multi-ply. The biggest disadvantage seen in this alternative is the two-step process itself, which is inherently inefficient. In addition, the double process increases knitting thread usage and exposes the raw material to additional wear and possible damage.

The productivity of this method can be clearly increased when two work areas are combined one after another in a single machine. This allows the process to be shortened to one step (Alternative 3b). Anon. (2000) presented an example of such a solution for special stitch-bonding machines for non-woven fabrics, analogous to the solution presented (Anon., 1994) for reinforcing non-wovens. However, to ensure the free positioning of the warp layers in multi-plies, it is necessary to either turn the multi-ply between the two work stations, or to install the second work station in reverse over the first one. This solution still does not address increased knitting thread usage and additional wear of the raw material.

After considering the alternatives and solutions to freely position multiple layers in multi-plies, it seems that the method of shifting the needle loops and following with the binding off (in short the needle-shift technique) proves to be the most promising development. We will now examine the effects of this additional processing step on the construction of the pattern and the multi-ply itself.

Expanded stitch-bonding process

Technological implementation of the expanded stitch-bonding process

The main objective in the development of the expanded stitch-bonding process is to ensure free positioning of individual layers; especially those of the warp-thread layers on both outer sides of the fabric (Hausding et al., 2006, 2007; Hausding, Widulle, Paul, & Cherif, 2008).

Forming the basis of the needle-shift technique is the additional movement of the compound needle in a right angle perpendicular to its standard movement during the knitting cycle in the stitching process (Anon., 2003a, 2003b). On a knitting machine, the compound needle and the wire tongue only move up and down perpendicular to the raw material. In the shift technique, a lateral movement of the compound needle and wire tongue is added (Figure 2), in order to transfer the knitting thread according to pattern on the side of the fabric away from the guides.

The patterning devices for the shift of the needle bar correspond to that of the guide bar. A cam disk or linear drives can guide the shift movement. When considering patterns, we assume that there are countless pattern variations that can be realised, as is common with a linear drive.

In previous studies (Hausding et al., 2008), it has been proven that symmetrical layer positioning in the form of ($0°/\Theta°/\Theta°/0°$) can be manufactured and successfully reproduced using this technique (Figure 3). Such multi-plies are used in reinforced plastics and due to the symmetrical layer constellation, successfully minimize deformations caused by residual stresses in the construction members.

Modification to the manufacturing process affects the pattern construction considerably. On the one hand, the number of possible patterns increases, and on the other hand, common approaches and procedures to diagram the patterns, both graphically and numerically, cannot be directly transferred without modifications to depict the expanded stitch-bonding process.

The pattern in the expanded stitch-bonding process

Diagramming the pattern with the needle shift technique

By including the shift movement of the needle, new requirements to illustrate the pattern must be met. The shift must clearly and correctly emanate from the graphic and numeric illustration. In addition, the graphic illustration should provide a clear image as to the appearance of the finished product. All illustrations and specifications for

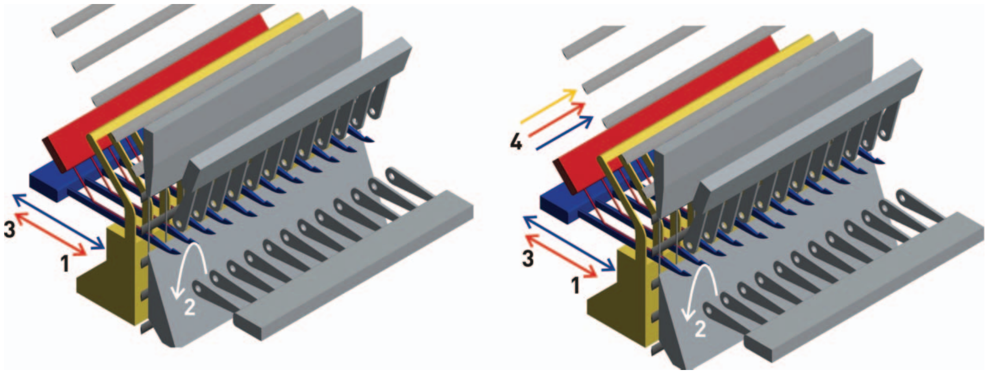

Figure 2. Movement of knitting elements on a stitch-bonding machine without (left) and with (right) shifting of needles. (1) Forward movement of compound needle and wire tongue, (2) thread insertion, (3) backward movement of compound needle and wire tongue, and (4) lateral shift of compound needle, wire tongue and knock-over sinker.

warp-knitted materials with a needle shift are oriented on standard illustrations and pattern descriptions of conventional warp-knitted materials.

The lapping diagram has been based up to this point on the illustration for the movement of the yarn guides, which are clearly marked by position numbers for the needle spaces. This clear location marking is lost in the needle shift technique since the needle spaces no longer remain in their fixed positions. To compensate, we have introduced a relative and an absolute position number. The absolute position numbers indicate the position of the needles when they are nearest to the pattern mechanism at "0" position (called absolute zero position). This is equivalent to the "0" position in conventional warp-knitting machines. When the pattern mechanism is mounted on the right side, the absolute "0" position is the outermost right position for the guide bar and the needle bar, and when mounted on the left side, it is the outermost left-hand position. The yarn guide on the furthest right is considered to be in the needle space "0". The absolute position numbers are the basis for controlling the movement of the guide bar, since they correspond to the standard needle space numeration and remain unchanged. Because the numbering does not change, it is inevitable that with the shifting of the needle the actual needle space location and their numeration no longer correspond to one another. Therefore, the relative position numbers are used to mark the actual position of the needle spaces. The relative numbers are each assigned to only one needle space and therefore their position may be changed (Figure 4).

The numerical description of the guide-bar movement is always relative to the absolute position numbers. These are also used to describe the shifting movement of the needle bar. With this modification, information is added to the lapping diagram (Figure 5). The lapping diagram for the needle bar is labeled with NB. Each knitting cycle is given two numbers. The first stands for the position of the needle bar before the swing-in movement of the yarn guide, the second for the position of the needle bar after the swing-out movement of the yarn guides. The second position of the previous knitting cycle is always identical to position one of the upcoming cycle. Since the pattern repeat for the needle-bar movement can begin in a position other than the absolute "0" position, it is necessary to assign a number to the first part of the knitting cycle. This is always

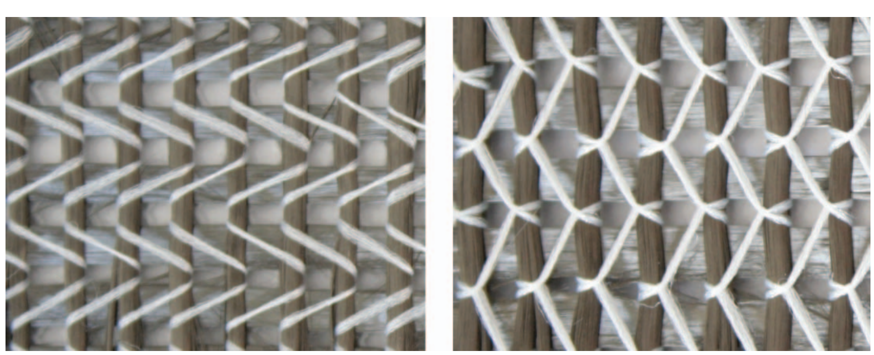

Figure 3. Face and reverse side of a biaxial stitch-bonded multi-ply, carbon fiber, [0/90/0], pattern: cord, basic offset 1 in the same direction.

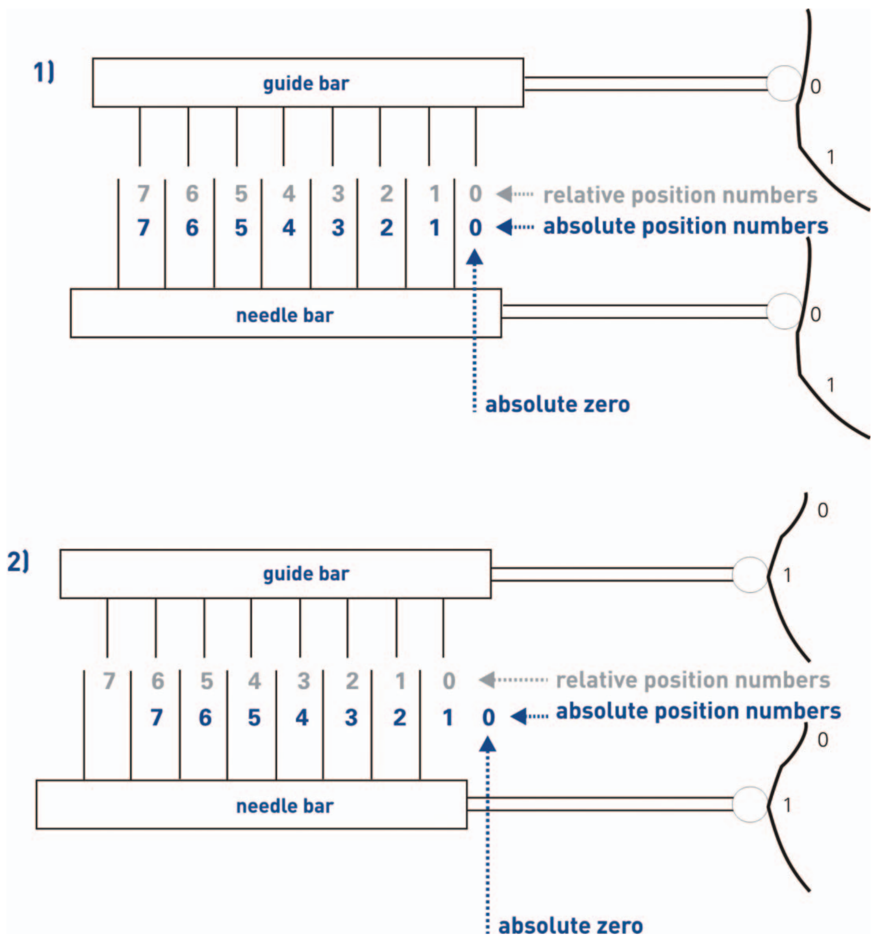

Figure 4. Definition: absolute and relative numeration of positions.

the case when the first shift in the pattern repeat begins in the direction of the absolute "0" position. Just as in the lapping diagram for the guide bar, a backslash represents the end of a knitting cycle, a double backslash for the end of a pattern repeat. The last number in the pattern repeat is always identical to the first number; the guide bar always begins with the first step after the last shift. The length of a pattern repeat for the needle bar can differ from that of the guide bar.

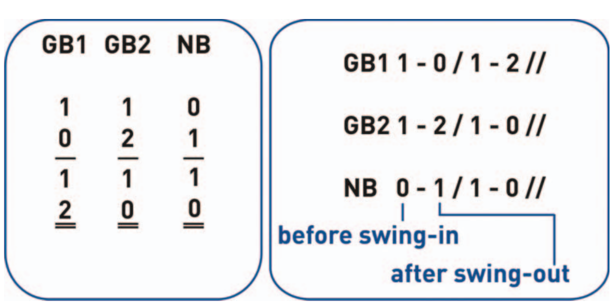

Figure 5. Lapping diagram with pattern repeat for the needle bar shift.

When the pattern repeat lengths for the guide bar and the needle bar differ, the repeat of the resulting pattern is the least common multiple of the two-pattern repeats. For example pillar stitch, open (1–0/0–1//) and the needle offset (1–2/2–0/0–1//), means the resulting pattern has a repeat of $2 \times 3 = 6$. The overlap and the shift are to be repeated until the calculated pattern repeat has been reached.

When using standard graphic diagrams, the actual position of the needle bar is not recognizable. When reading the diagram, the guide-bar course no longer depicts the actual threadline, nor does it relay information as to the actual appearance of the material.

Because of this, the lapping diagram is expanded to include additional information. An arrow is added to mark the width and direction of the offset (see Figure 6). Additionally, a needle in the first row is identified as a marker. This marking needle should be chosen so the arrow does not interfere with this row or any subsequent rows in the lapping diagram. The same marking needle should be used in each row. The point of the arrow shows the direction and the length of the arrow depicts the span of the shift that takes place after the guide-bar movement. The length of

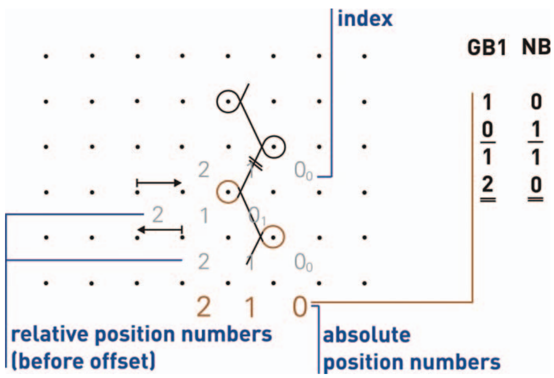

Figure 6. Lapping diagram with relative position numbers (pattern: tricot, basic shift 1 in the same direction).

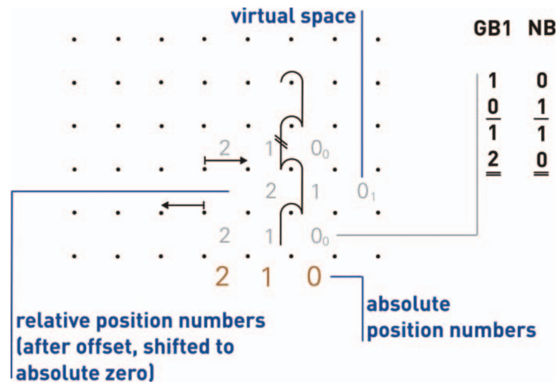

Figure 7. Lapping diagram with shifted relative position numbers (pattern: tricot, basic shift 1).

the arrow corresponds to the second number in the lapping diagram.

If the actual position of the needle bar is to be identified at the time of loop formation, then the relative position number must be given for each row. An example can be seen in Figure 6. Under the lapping diagram, the absolute position numbers are written and emphasized in a different font. Please note that in this type of lapping diagram, the overlaps, according to the chain notation, are given with the absolute position numbers. The relative position numbers are only used to clarify the needle-bar position. They are placed underneath the row of the first loop, and in each subsequent row shifted according to the needle offset. The shift arrow in the row above depicts the offset. In order to clearly mark the relative position of the needle spaces to the absolute "0" position, an index number is introduced. The index number marks the needle space "0" in each row thereby clearly showing the number of needle spaces the guide bar has shifted from absolute zero. The relative position numbers always depict the position of the allocated needle row before the placement of the guide – before the shift – which follows at the end of the knitting cycle.

For example in Figure 6, when defining the position of the needle bar relative to the absolute "0" position (the reference parameter for the guide-bar movement), it is clear that when shogging the needle bar from "0" to "1" and shifting the needle from "1" to "0" (absolute), the outermost yarn guide on the right has no needle to feed. The number of needles affected by this is shown in the lapping diagram. Furthermore, by introducing relative position numbers (see Figure 6) it is obvious that the tricot pattern depicted combined with this particular offset cannot be that of a standard tricot pattern. This is made obvious by the thread guide, which continually places the thread on the same needle. This type of illustration does not accurately depict the material's final appearance.

In order to create an approximate depiction of the material, the needles are shown as if they were returned to the absolute zero position at the time the loops are formed. This can be done with a lapping diagram where the relative position numbers are shifted to the "0" position. However, to guarantee a correct drawing of the overlaps, each needle space is labeled with the relative position number that it occupies at precisely that moment (see Figure 7). This means that the needle space numeration in each row corresponds to the actual needle location at that given point. However, its position corresponds to that of the needle position in the absolute "0" position. The numbers on the lapping diagram always refer in this chain notation to the relative position numbers in each corresponding row and no longer to the absolute position numbers. Since the relative position numbers are no longer depicted in their offset position, they are determined in the following manner: they are calculated by adding (shift arrow points left) or subtracting (shift arrow points right) the position number of the previous row with the shift width (length of shift arrow). The relative position numbers always begin at "0". However, it is necessary to consider that all relative position numbers beginning to the right of the absolute "0" position are only virtual. At the time of loop formation, no needles are located here (see also Figure 8).

The lapping diagram with the shifted relative position numbers allows for an approximate illustration of the threadline in the material, however, the actual movement of the thread guides is not recognizable. It is the chain notation that is always decisive for guiding the machine.

Equivalent patterns

In general, an analogous pattern without a needle offset exists for all RL patterns with a needle offset. In other words, for every pattern with a needle offset there is an equivalent pattern with a similar structure produced without a needle offset. They are comparable with regard to the length of the underlaps in the textile.

The equivalent pattern is not necessarily evident from the chain notation for the guide bar and needle bar.

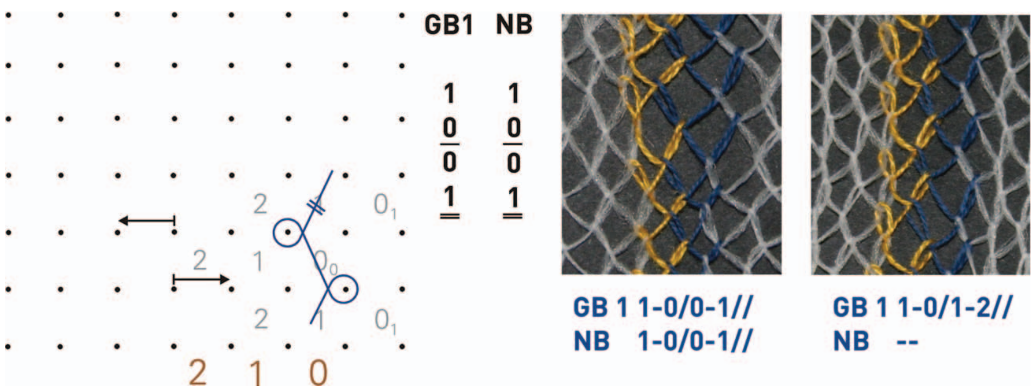

Figure 8. Lapping diagram (left) with comparison to equivalent pattern (right): open-lap pillar stitch, basic offset 1 in the same direction.

However, it is recognizable from the lapping diagram with the shifted relative position numbers (see Figure 7). The lapping diagram of the equivalent pattern can be calculated from the chain notation as follows (Equation (1)):

$$\begin{pmatrix} a_{\mathrm{GB}} \\ b_{\mathrm{GB}} \end{pmatrix} + \begin{pmatrix} G_{\max} \\ G_{\max} \end{pmatrix} - \begin{pmatrix} a_{\mathrm{NB}} \\ a_{\mathrm{NB}} \end{pmatrix} = \begin{pmatrix} a'_{\mathrm{GB}} \\ b'_{\mathrm{GB}} \end{pmatrix}, \tag{1}$$

with

a_{GB} start overlap guide bar,
b_{GB} end overlap guide bar,
a'_{GB} start overlap guide bar (Equivalent Pattern),
b'_{GB} end overlap guide bar (Equivalent Pattern),
a_{NB} position of the needle bar at time of overlap,
$G_{\max}$ maximum number of virtual needle spaces in use.

The $G_{\max}$ value, the maximum number of virtual spaces used in the pattern, can be calculated by subtracting the smaller value of the coinciding overlaps of the guide bar from the maximum offset value (positions) of the needle bar, $V_{\max}$ throughout the complete pattern repeat. $V_{\max}$ is always the first value in the matrix of the needle bar offset. Should the value $V_{\max}$ be present more than once in the pattern repeat, then $G_{\max}$ is the largest difference of all the $V_{\max}$ values calculated for G. The $G_{\max}$ value cannot be less than zero (0). If the smaller value of the corresponding overlaps is larger than $V_{\max}$ then $G_{\max}$ is zero (0).

This calculation must be implemented for each overlap in the pattern repeat. If the pattern repeat for the needle bar is longer than that for the guide bar, then the pattern repeat for the guide bar begins anew until the needle-bar pattern repeat has been completed. The opposite is true should the guide-bar repeat be longer than that of the needle bar. Following is an example of the calculation taken from Figure 7 for a tricot pattern:

The chain notation for the guide bar is as follows: 1–0 / 1–2 //.
The chain notation for the needle bar is as follows: 0–1 / 1–0 //.

The equivalent pattern is calculated as demonstrated in Equation 2,

$$\begin{aligned} \begin{pmatrix} a'_{\mathrm{GB}} \\ b'_{\mathrm{GB}} \end{pmatrix} &= \begin{pmatrix} 1 \\ 0 \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \end{pmatrix} - \begin{pmatrix} 0 \\ 0 \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \\ \begin{pmatrix} c'_{\mathrm{GB}} \\ d'_{\mathrm{GB}} \end{pmatrix} &= \begin{pmatrix} 1 \\ 2 \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \end{pmatrix} - \begin{pmatrix} 1 \\ 1 \end{pmatrix} = \begin{pmatrix} 0 \\ 1 \end{pmatrix} \end{aligned} \tag{2}$$

with

$$\begin{pmatrix} a_{\mathrm{GB}} \\ b_{\mathrm{GB}} \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$
$$\begin{pmatrix} c_{\mathrm{GB}} \\ d_{\mathrm{GB}} \end{pmatrix} = \begin{pmatrix} 1 \\ 2 \end{pmatrix}$$
$$a_{\mathrm{NB}} = 0$$
$$c_{\mathrm{NB}} = 1.$$

The maximum offset value, $V_{\max} = 1$, of the needle bar is reached in row two. The corresponding overlap is 1–2. The smallest value of the overlaps therefore is $c_{\mathrm{GB}} = 1$. The number of virtual spaces occupied, $G_{\max}$, is calculated as per Equation 3,

$$G_{\max} = V_{\max} - c_{GB} = 1 - 1 = 0. \tag{3}$$

The equivalent pattern for tricot with a needle offset of (0–1 / 1–0 //) is that for an open-lap pillar stitch.

Basic patterns in combination with a needle offset

Allocation and criteria

All known patterns can be combined with a needle offset. The possible offsets for the needle bar can be allocated as follows based on typical applications:

(1) There is no offset. This means, the produced pattern is equivalent to the conventional RL-basic pattern (zero offset).
(2) The offset occurs at regular intervals in each row and

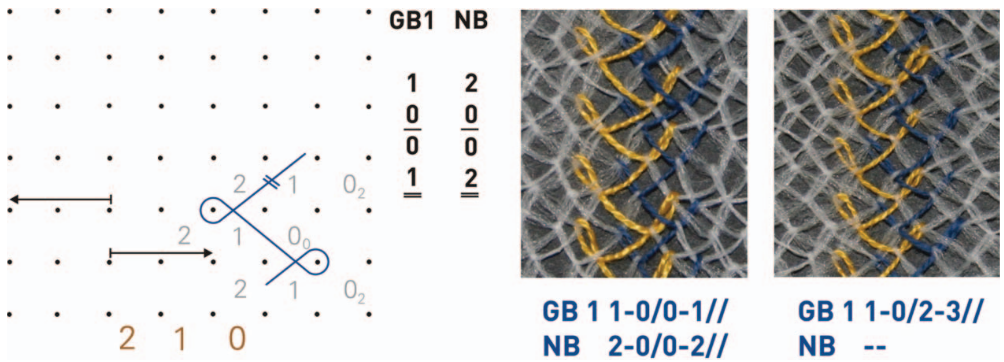

Figure 9. Lapping diagram (left) with comparison to equivalent pattern (right): Open-lap pillar stitch, basic offset 2 in the same direction.

- the shift direction changes in each row whereby the shift width remains the same (basic offset),
- the shift direction changes in each row and the shift width is irregular (irregular basic offset),
- the shift direction changes after n rows and the shift width remains the same, where $n \neq 1$ (diagonal offset),
- the shift direction changes after n rows and the shift width is irregular, where $n \neq 1$ (irregular diagonal offset).

(3) All other offset variations are categorized as an irregular offset and include such shifts as:

- the shift occurs multiple times in the same direction with a change after an irregular number of rows, or
- an irregular shift with varying shift widths.

It is also necessary to differentiate in which direction the needle bar shifts in relation to the guide bar(s) (relative direction):

- Same direction – the needle bar shift follows the same direction as the underlap of the guide bar.
- Opposite direction – the needle bar shift follows the opposite direction as the underlap of the guide bar.

When the guide bar underlaps and the needle bar shifts change at regular intervals in each row or are otherwise constant relative to one another, then the allocation of the relative direction applies to the complete pattern. The relative direction of the needle-bar offset is always assigned in relation to the guide bar 1 (GB 1). When multiple guide bars are present, the relative direction for the other guide bars is then obvious. For example, when in the pattern double tricot is in opposition, the needle bar moves parallel to GB 1, then it follows that the movement in relation to GB 2 is in the opposite direction. However, when the guide bar overlaps and the needle shifts are irregular in their relative direction, then the terms parallel and opposite can only be applied for each individual row and are not to be applied to the complete pattern. In such a case, the relative direction, when not noted otherwise, always refers to the first underlap in the pattern.

Another characteristic of the needle offset is the shift width in each row. In this paper, we consider a maximum shift width of four. The shift width is given in the pattern description as a number with basic offset (i.e. basic offset 2). In patterns with a diagonal offset, the shift width is given after the marking for the number of rows n, after which the direction changes (i.e. diagonal offset 4–2; directional change after 4 rows, in each row a shift width of 2). The following examples are patterns where the guide bars and needle bar move in a regular pattern.

Pillar stitch

The combination of pillar stitch and needle-shift patterns always results in a fabric (as opposed to the conventional pillar stitch which does not produce a fabric). The combination of an open-lap pillar stitch with basic offset renders an equivalent pattern to that of the patterns tricot, cord, satin and velvet (examples in Figures 8 and 9). When the needle shift runs in the same direction (in the absence of underlaps relative to the overlaps) closed loops are produced and by an opposite needle shift open loops. The patterns with a needle shift in the same direction are mirror images to those with an opposite needle shift.

The combination of closed-lap pillar stitch and a basic offset results in patterns equivalent to tricot, cord, satin and velvet patterns, where each has an open loop and a closed loop since the relative direction changes in each row. In changing shift directions, a mirror image of the pattern is created where the sequence of open and closed loops is shifted up or down a row.

Tricot, cord, satin and velvet

By combining the basic patterns tricot, cord, satin and velvet with a basic offset, equivalent patterns to the patterns pillar stitch and others ranging from tricot to velvet are created,

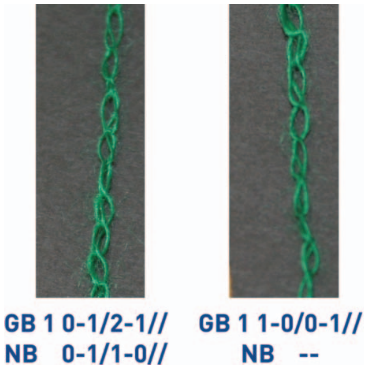

Figure 10. Tricot, basic offset 1 in the same direction and comparison to equivalent pattern.

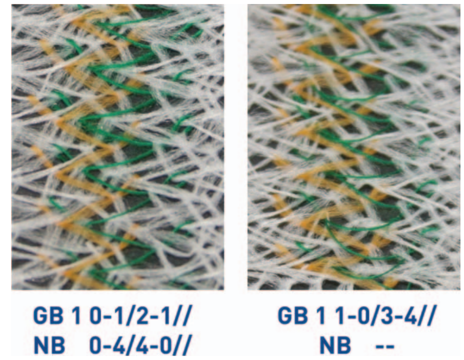

Figure 12. Tricot, basic offset 4 in the same direction and comparison to equivalent pattern.

as well as patterns with underlaps covering more than four needle spaces.

In patterns with an offset in the same direction the equivalent patterns can be categorized as follows:

- When the needle-bar shift width is the same as the guide bar shift width, then the equivalent pattern open-lap pillar stitch is always created (Figure 10).
- When the needle-bar shift width is smaller than that of the guide bar, then the equivalent patterns tricot (shift width is one space less), cord (shift width is two less) and satin (shift width is three less) are created. The loops remain the same.
- When the needle-bar shift width is greater than that of the guide bar, then the equivalent patterns tricot (shift width is one space more), cord (shift width is two spaces more, Figure 11) and satin (shift width is three spaces more; see Figure 12) are formed. Open loops become closed loops and the opposite is true for the closed loops.

When the needle-bar and guide bar shifts are in the opposite direction then the equivalent pattern is increased by the shift width of the needle bar. For example, from tricot the equivalent patterns are cord (shift width one, Figure 13), satin, (two) and velvet (three). The loops remain in an open pattern open and in a closed pattern closed.

Summary

The expanded stitch-bonding process extended to include a shift of the needle bar makes a free positioning of layers in multi-plies achievable. It is now possible to produce symmetrically arranged multi-plies [0°/Θ°/Θ°/0°] in a single step, independent of the restrictions of standard knitting patterns. Deformations caused by residual stresses in reinforced plastic composites can now be avoided. However, by implementing the new production step, there are extensive ramifications on the present stitching patterns. The patterns produced with the new extended stitching principles require new methods of diagramming and numerical notation. The lapping diagram and the chain notation need to provide supplemental information. From these new diagramming and numerical techniques, equivalent patterns, based on the conventional warp-knitting techniques, are created and are equal to the new patterns. With the help of an equation, it is also possible to mathematically

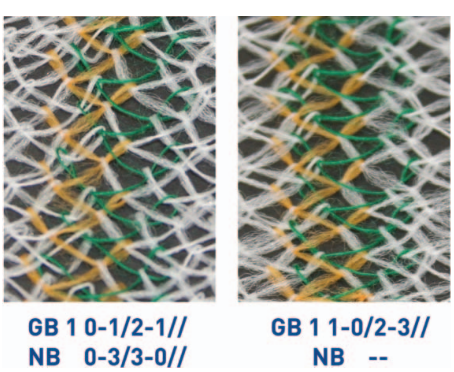

Figure 11. Tricot, basic offset 3 in the same direction and comparison to equivalent pattern.

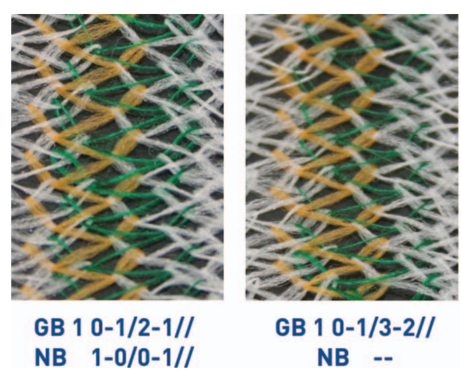

Figure 13. Tricot, offset 1 in opposite direction and comparison to equivalent pattern.

calculate the equivalent pattern based on the chain notation. All known patterns in the conventional warp-knitting process can be combined with the expanded stitching process, whereas the new patterns can be developed from the corresponding established conformities found in the two original patterns.

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