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ON THE IN-PLANE DEFORMABILITY OF CROSS-PLIED UNIDIRECTIONAL PREPREG

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Abstract

The work presented herein aims to investigate the in-plane properties of cross-plyed unidirectional prepreg using the bias extension method. The study is focusing on different generations of carbon fibre/epoxy material systems and testing is performed at elevated temperatures to enhance formability. Using digital image correlation (DIC), the specimen deformation and fibre rotation is captured during tests. The study shows that most cross-plyed unidirectional material deforms at different characteristic length scales as deformation continues: first seemingly continuous and later in form of bands.

Further, the different type of prepreg materials investigated behaves differently; for one type the pin-jointed net theory fit well, enabling simple estimation of resulting fibre angle, while for the another two not. Different loading speed and temperatures are investigated in order to pin-point its influence on the deformability.

Keywords: forming mechanisms, thermoset prepreg, carbon fibre composites, intraply deformation, bias extension test

1 Introduction

Aerospace composite manufacturer are always striving towards achieving a high quality at lowest possible (affordable) weight. To achieve this, unidirectional (UD) carbon fibre prepreg (preimpregnated fibres) is one of the common choices of material. A manufacturing method still commonly used is hand lay-up, i.e. placing each layer of prepreg onto a mould by hand; a very time consuming process. To lower the cost of composite components, attempts to automate parts of the manufacturing process are made. The automatic tape layer (ATL) offers interesting and promising solutions for manufacturing of fairly simple geometries. However, when it comes to producing laminates with complex shape these methods can not yet do the work themselves.

A promising manufacturing method for automated shaping of thermoset composites with continuous fibres is sheet forming [1-3]; a method until recently mostly used for thermoplastics. The process can be described as the forming of planar sheets of pre-stacked laminates into more complex shapes, usually by using moulds or different kinds of tools. The pressure that forces the sheet to deform can be applied by e.g. matched dies or a compliant diaphragm. Since the process forces the pre-stacked and initially flat material to stretch, slide and be compressed to the requested geometry, the process raises new demands on the deformability of the prepreg material.

The deformation behaviour of dry woven fabrics is highly shear-dominated and commonly described as a pin-jointed net (PJN), meaning that it deforms through rotation at the cross over points between warp and weft [1, 4-6]. Cross-ply UD prepreg may show similar deformation behaviour to woven fabrics [7]; however, since cross-ply lack the physical links of a weave, the complete deformation is more complex. In previously published studies, the possibility of increased drapability of cross-ply UD prepreg compared to woven fabrics has been noted, but at the same time

cross-ply UD prepreg has still often been considered to undergo deformation seemingly following the PJN approximation. Including slippage as a forming mechanism may increase the forming limits of a material system; however, it also imposes difficulties in predicting forming limits and final fibre angles [8]. Since the forming limits will decide the feasibility of manufacturing certain geometry with a specific material and stacking sequence it is important to be able to characterise them. The final fibre angles will affect the cured mechanical properties and the possible shape distortion. This motivates further work in the area.

The aim of this study is to investigate the in-plane forming behaviour of different generations of aerospace certified, UD prepreg material systems. These material systems have shown totally different forming behaviour in the workshop, but are similar according to cured properties. The study is experimental and restricted to in-plane behaviour of cross-ply UD prepreg. In parallel, the interply friction between the separate layers has been experimentally studied by the authors [9]. The fundamental aim of the work presented herein is to observe the mechanisms occurring during in-plane deformation and compare the behaviour of the three material systems considered. This will be done by bias extension test in combination with the contact free measuring system called digital image correlation (DIC). The methodology enables measurements on the fibre angle rotation during deformation, as well as the load response. By studying the photos, the evolution of different deformation mechanisms can be followed until failure, as e.g. prepreg wrinkling.

2 Theory

In most drape predictions the reinforcement is assumed to be inextensible. Considering that the matrix (especially in its uncured state) is so much weaker than the fibres, this can be seen as a valid assumption. Consequently, the deformation has to take place

transverse to the fibre direction and within the matrix, i.e. inside and in-between fibre tows and prepreg layers. The known deformation modes for a stack of prepreg with continuous fibres are interply (between layers), intraply or trellis (within layers), resin percolation and squeeze flow [10]. In this study the deformations are obtained without large pressure gradients perpendicular to the surface and using resin starved (non-bleeding) prepreg materials, wherefore the level of resin percolation and squeeze flow is limited. To focus is therefore on the intra- and interply deformation.

The PJN approximation was initially proposed by Mack and Taylor [4] and has thereafter been developed and widely used, e.g. [6-8, 11, 12]. The theory includes the assumption that the fibres are considered to be inextensible and seen as lines, i.e. with no thickness and width. In addition, there is no slippage allowed at cross-over points, but the fibres can rotate freely. Implicitly this results in that there is no resistance to lateral bending, i.e. the fibre can have different angles on each side of a cross-over. Due to the restriction on slippage at cross-over points, the area captured in-between crossing fibres (in the plane) ideally goes to zero as deformation continues, which put a compacting force on the material. This limits the maximum deformation allowed before wrinkling or other undesired out-of plane deformations to appear. At this deformation level, the load to deformation is rapidly increasing. For weaves, a shear locking angle, also referred to as a maximum shear angle, can be defined as the limit of in-plane deformation [13]. Moreover, for weaves the width of the fibre tows and the weaving pattern itself makes the cross-over points well defined and fairly sparsely distributed. In fact, for cross-ply UD prepreg, the cross-over points can be of several length scales and possibly change during forming. Examples of these scales can be single fibre, fibre tow or even determined by the comb teeth used when producing the prepreg material. Increasing the distance between cross-over points, a larger area can undergo compaction

[14]. However, the energy required to overcome friction and rotate at cross-over points, increases with cross-over area (due to higher preferential rotational velocities), see Figure 1. If each fibre is considered a cross-over point, the area and preferential rotational velocity at the cross-over point is negligible. It is therefore assumed that the dominating length scale during deformation of cross-ply UD prepreg depends on which deformation mode requires least energy: interply friction for the larger cross-over scales or intraply deformation as the cross-over points are defined by the fibre or fibre tow size. For material behaving similar to what is expected from the PJN theory, the latter includes in-plane fibre tow compaction. Harrison et al. [15] models a weave with a constituent-based approach by using the rheology of a viscous textile. This continuum model describes the meso level of deformation both within fibre tows and matrix. Also, prediction of a shear locking angle can be made. According to this model the most significant parameters are viscosity and fibre volume fraction. For cross-ply unidirectional prepreg there is no equivalent to the shear locking angle of a weave; instead, the limit of deformation can be wrinkling or breakage of bonds between fibres.

While several test methods have been developed to measure intra- and interply shear, e.g. picture frame [11, 12] for pure intraply properties and “interlaminar pull-out test” or “lap shear test” [2, 15, 16] for pure interply properties, the real deformation of a cross-ply UD prepreg is rather a combination of the two [7]. Comparisons between bias extension and picture frame test methods can be found in [11, 12], where it is shown that picture-frame is sensitive to fibre misalignment. For the bias extension test there can be problems to get precision in the measurement of fibre angle and a low viscosity can make the test fall under its own weight. The bias extension test used in this study is an off-axis tensile test that can be used to measure intraply shear properties, while allowing potential slip. Intraply slip can either occur as ‘cross-over’ or ‘inter-tow’

[12]. To achieve a uniform shear zone, a symmetric cross-ply or weave is located 45° off-axis compared to the tension direction. The bias-extension test has been shown to be difficult to use for characterising of UD reinforced thermoplastics due to its low integrity at high temperatures, which results in large scatter [17].

An idealised bias-extension test is illustrated in Figure 2 with schematic figures of both undeformed and deformed specimens according to the PJN theory. The PJN theory predicts three different zones within the specimen; A, B and C. According to theory, zone A is where the shear is uniform and a theoretical rotational angle, θ , can be calculated according to Equation (1) [11]. In zone B the shear angle is half the angle in zone A and zone C should ideally remain undeformed. The piece to the right in Figure 2 is deformed a distance d and has a total length of:

$$L_d = W + 2(L - W)\cos \theta_0 \cos \theta \quad (1)$$

where W is the initial sample width, L the initial sample length, θ_0 the initial fibre angle and θ the instantaneous fibre angle during deformation.

The bias-extension test is herein used to characterise the forming behaviour of cross-ply UD prepreg; note that this test method corresponds to forming at tension in the plane. This differs to what occurs during normal hand lay-up, which rather includes piecewise folding of the material onto the tool starting at the first point of contact. During diaphragm forming, the prepreg material is partly clamped in-between flexible diaphragms and the friction transfers the force to the prepreg laminate. For sheet forming under a single flexible vacuum bag, the lamina is less clamped. However, in-plane deformation tension is still important as it enables forming of piecewise concave geometries.

3 Experimental methods

3.1 Material

The three studied materials are unidirectional, aerospace graded carbon/epoxy prepreg: Cycom 977-2 with HTA fibre from Cytec with a nominal ply thickness of approximately 0.14 mm and a fibre volume fraction of $58 \pm 5\%$ and Hexply/M21/35% with T700 fibre from Hexcel with a nominal ply thickness between 0.30 mm and 0.32 mm. The latter material has a volume fraction of fibres equal to 57%. The third material is Hexply 8552 with an AS4 fibre from Hexcel and a measured ply thickness is 0.15mm. The material is commercially available with a volume fraction of fibres of 57%, but the herein tested material is specified by Saab Group AB and has a slightly higher volume fraction (not given due to company agreement). The three materials are herein referred to as 977-2, M21 and 8552.

One major difference between the prepreg systems is the fibre/matrix distribution within the prepreg. The distribution is partly determined by the type of tougheners used; M21 include thermoplastic particles while 977-2 and 8552 uses a liquid thermoplastic toughener. Due to the thermoplastic particles, the surface area the thermoset resin needs to cover is larger for the M21 material, which gives that prepreg system a dryer feeling. Further, the particles in the M21 material makes the interply interfaces (with particles) more resin rich, forcing a locally higher volume fraction of fibres within and between the fibre tows, see [18, 19] for further details.

An experimental investigation of the interply friction between two prepreg layers sliding pass each other have shown that the frictional resistant for M21 is approximately 10 times larger than for 977-2 [9]. Further, the study [20] shows that 8552 has interlaminar frictional properties in the same range of M21, but a different trend according to changes in viscosity. An increased viscosity, i.e. a lower temperature, gives an increased friction for 8552, whilst for M21 the friction seems almost constant. From

the viscosity curves (given by the material suppliers) some approximate values are extracted and show that 977-2 and 8552 are in the same order of magnitude for the temperature interval 60-85°C, see Table 1. M21 including particles has a significantly higher viscosity. These results indicate that the interlaminar friction is not only driven by the matrix viscosity, but also the surface structure and ply architecture.

3.2 Equipment

An Instron 4505 machine equipped with a 5kN load cell was used for all tests. The software used was Cyclic version 7.07.03 from Inersjö Systems AB. The specimen was held in place with pneumatic grips with a clamping force of 1kN. To control the temperature an environmental chamber surrounded the test set-up. The environmental chamber is customer built by Elastocon AB to suit Instron 4505 and can be used within a temperature interval of -40 to 300°C.

To calculate strain and follow the rotation of fibres, an image processing technique called digital image correlation (DIC) was used. For this, a software for optical 3D and 2D deformation analysis, Aramis provided by GOM [21], was used. The system is suited to measure three-dimensional deformation and strain, but due to difficulties with the calibration through the glass window of the environmental chamber, only 2D deformation analyses were made within this study. For the present study, the facet size (a group of measuring points) was never less than 2.5mm. The resolution of the camera used was 1.3MP.

3.3 Sample preparation

Each specimen consisted of four cross-ply prepreg layers, [+45/-45]_s. To achieve a well controlled thickness the hand laid pieces were vacuum consolidated at room temperature for at least 30 min at -1 bar pressure.

All specimens were of the same size and had an ungripped sample length $L=250$ mm and initial width $W=50$ mm. The effective length, L_{eff} , (the part deforming during test) is $L - 2 \cdot \frac{W}{2}$; this due to the $\pm 45^\circ$ lay-up and the triangles at each end that remain undeformed, see Fig. 2. The test piece should have a ratio length to width ratio larger than two to experience a relatively uniform shear zone A [6]. The samples tested in this study have a ratio of 5. The tested specimens had different thickness; M21-specimen consisted of four layers of approximately 0.31 mm thick laminas while 977-2 and 8552 had four 0.14 mm thick layers. After cutting, lines for visual inspection of the deformation were painted onto the surface (using a ruler and a white liquid pen) to mark out the middle of the specimen and the borders of the idealised shear zones, as in Figure 2. To enable Aramis to register the deformation a stochastic pattern called speckles was applied to the surface of the sample.

3.4 Test series

In this first study, since the actual deformation modes are not known, testing temperatures were set based on experiences from the workshop during real forming operations [22]. Therefore, 977-2 was tested at a temperature of 70°C ; a temperature known to provide good forming properties. According to experience, M21 requires a higher forming temperature than 977-2, wherefore it was tested at 85°C , but to be able to compare the systems, tests were performed at 70°C as well. 8552 was chosen to be tested at 45°C and 70°C to see how the large change in viscosity affected the forming behaviour. In order to prevent non-preferred cross-linking (curing), no temperatures higher than 90°C should be used [22].

The influence of an increased strain-rate was tested by performing tests at different cross-head speeds, providing a wide test range covering all rates possible to achieve for

most forming techniques. The cross-head rates tested was between 5 mm/min and 200 mm/min. All test combinations are presented in Table 2.

3.4 Evaluation of test results

Due to the difference in sample thickness for the different material systems tested, the load response is normalised with respect to thickness to simplify comparison. The results were filtered with a butterworth filter to get rid of the noise. As seen in Figure 3, the low loads registered in the case of 977-2 results in more noisy response compared to the 8552 materials much higher level of load.

Although the measured loads sometimes were fairly low and noisy, the results were remarkably repeatable. A typical example, the spread from four tests of 977-2 at 70°C and 40 mm/min is showed in Figure 4. The results are presented as load-displacement curves, which corresponds to the recorded values during the test. The strain can be calculated based on the deformations registered with the DIC equipment; however, large deformations and reflections in the surface of the specimen made it difficult for Aramis to keep track of the sample at large displacements. This resulted in a loss of measuring points, and no calculations were possible to obtain after a certain distance (varying between tests).

The fibre rotation during deformation was determined using the Aramis software [21]. The fibre rotation was measured by marking two facets on either side on the central line and drawing an imaginary line in-between them, representing the original fibre direction [18]. By following these facets (the line) during deformation, the change in fibre angle could be determined, see Figure 5.

The automatically generated results obtained from the Aramis software was complemented with manual measurements with ImageJ®, on the photos acquired from

the tests. These photos were for example used to determine the wrinkling onset and the different deformation modes using visual inspection.

The manually measured sample width gives further information on the type of intraply shear occurring, i.e. for deformation according to the PJN theory the sample width must reduce correspondingly. However, for samples undergoing partial slip, the degree of material compaction is less and consequently the reduction in sample width during deformation is smaller. Measuring the instantaneous sample width during testing thereby offers a mean to verify the automatically generated results obtained from the software. This has been used during the initial trials to verify the methodology.

4 Results and Discussion

The results from the bias extension test are presented in terms of maximum deformation level, load response and finally fibre rotation. The bias-extension test is used to investigate some of the mechanisms that occur during forming and to compare the material to each other.

The results are either presented with the displacement or the strain; where the displacement is the movement of the cross-head and strain is given by Equation (2).

$$\varepsilon = \frac{\Delta}{L_{eff}} \quad (2)$$

where ε is the engineering strain, Δ is the displacement and L_{eff} is the effective deformation length ($L-W$).

4.1 Deformation limits

The common flaws coupled to prepreg forming are fibre misalignment, in-plane fibre buckling, laminate wrinkling and an undesirable change in thickness [1]. Wrinkling was the most common flaw during bias-extension test for 977-2 and 8552, which is herein

defined as visible out-of-plane roughness as the fibre bundles starts climbing on top of each other [18]. The deformation at wrinkling initiation (for 977-2 and 8552) was determined by studying the pictures from the DIC. Wrinkling initiation is marked in the load-displacement curve shown in Figure 6 and 7.

For M21 the final deformation limit was splitting, see Figure 8, which occurs when the bond between fibres is broken. This seems to happen when the force required to rotate is larger than the friction between the layers.

Most of the tested samples showed similar evolution during the bias-extension testing: During the first phase, deformation was seemingly continuous and the sample centre line was neither tilted nor broken. Thereafter, the centre line was broken up into bands. Resulting band formations can be seen in Figure 9. The onset of band formation was different between the material systems, where 977-2 was deformed continuously at a higher level of displacement. The 977-2 showed band formation at approximately 13mm (6.5%) of deformation, whilst the M21 broke up earlier. 8552 tested at 70°C formed wider bands than the other materials; although at approximately the same displacement as M21, see Figure 7. The exception was the samples of 8552 tested at 45°C where no band formation occurred, but instead the fibres change to a s-shape in the plane. The result for M21 can be seen in Figure 10 and for 977-2 in Figure 6, where the transitions are marked by symbols. The first transition is the onset of breaking of the line marked on the middle of the sample (shown by diamonds) and the development of distinct bands is noted by the circles. Splitting of the sample (for M21, see Figure 8) or wrinkling initiation (for 977-2 and 8552), can be seen as the limit of deformation and is marked by stars. M21 specimens showed splitting of bands at approximately 25% elongation and in several places at the same time; see Figure 10.

It is interesting to note the influence of deformation speed on the band width: For 977-2, the width of these band depended on strain-rate; a slower rate resulted in wider bands (see [18, 19] for further details). Earlier published results [9] show that the interply friction coefficient increases with increased deformation rate for 977-2. Since larger bands results in higher preferential velocities at the interply area, see Figure 1, these results indicate that a transfer in length scales, to allow for interply friction, is at seemingly constant energy. Further experiments and measurements of the developed length scales are needed to verify this behaviour.

M21 behaves differently and the band width seems to be constant and independent of deformation rate in the tested interval. Measurements on the interply friction of M21, presented in [9], show that the friction is fairly constant with increased rate of deformation, whilst for 977-2 the load increases with increased rate. It seems like the reduced interply friction at higher velocities partly compensates for the increased rotational energy due to higher speeds and that the band width therefore is seemingly constant. In [7] Potter discusses the influence of the resin rich areas between the tows and claims that a great bulk of the deformation takes place there. The tow width for M21 is approximately 1.5mm and the band width is probably a multiple of tows, due to the lower intraply friction between the tows.

The maximum elongation before wrinkling for 977-2 is in the interval 10-25% (based on an effective deformation zone of 200mm). As presented in Figure 6, loading at a lower rate, a significantly higher deformation level could be reached before wrinkling initiation. Since a lower deformation rate results in wider slip-bands, the results indicate the wider slip-bands are more forgiving and enable higher deformation before wrinkling. For M21 is the effect of a change in the rate of deformation is smaller;

the load is higher for a faster rate, but the band width and the limit of deformation are more or less unaffected.

4.2 Deformation loads

The force required to deform the bias-extension specimens is shown to be strain-rate dependent: the higher the strain rate, the higher the load is required. This holds for both 977-2 and M21, for the strain-rate dependency of see Figure 6 and 10, respectively.

Note that the 977-2 material is tested at 70°C, while the M21 material is tested at 85°C. However, the same trend could be seen for all tested temperatures [18].

The forming properties of 977-2 are known to be good. The material can be formed even at room temperature with a successful result [18, 19]. Already from comparing Figure 6 and 10, it is obvious that M21 requires much higher loads to enable forming. The load is often more than three times higher for M21 compared to 977-2.

Figure 11 shows the effect of a temperature change during forming of the M21 material. The load is reduced with 25% when increasing the temperature with 15°C, from 70 to 85°C (i.e. when reducing the matrix viscosity from 300 Pa·s to approximately 90 Pa·s). A temperature variation within the stack during forming can affect where the sliding starts and thereafter propagates. This can result in through thickness variation of the forming and cause initiation of wrinkles, in for example corners.

When comparing the material systems load response there is a significant difference in load level, see Figure 12 8552 shows the largest resistance to deformation and as seen with the DIC the strain is not uniform. M21 requires less than half the load of 8552, but still around four times higher than 977-2.

4.3 Fibre rotation

Figure 13 shows a comparison between theoretical fibre rotation using PJN approximation and experimental measurements for the 977-2 prepreg material. The discrepancy is significant; meaning that the fibre rotation is approximately 30% less than theoretically predicted by PJN. These results strongly indicate that other deformations mechanisms than fibre rotations are active when deforming the 977-2 material. Since the study considers only in-plane deformation and the samples remain symmetric around its vertical central line throughout the tests, interply slippage seems to play an important role.

M21 shows a more predictable behaviour in the case of the fibre rotation (see Figure 14) and all samples tested follow the PJN approximation almost perfectly. Here; only the first 20mm is reported, this due to loss of data points for the DIC. Manual measurements confirm the correlation to the PJN theory up to 40mm of displacement (20% elongation), thereafter that the rotation is less than the theoretically predicted. Note that Figure 14 only shows the behaviour at one temperature; however, the same correlation between measured fibre rotation and the PJN theory could be observed for all other temperatures and lay-up methods tested [18].

Due to non-uniform strain fields when testing 8552, see Figure 15, the measurements were dependent on initial point of measure and are not showing the true fibre rotation. The contraction of the width was shown to be less than theoretically expected, whilst the fibre rotation could be both over and under predicted compared to the theory. The over prediction is not possible if the material would deform uniformly, which concludes that these samples behave non-uniformly. The very high volume fraction of fibres and tight packing give little space for compaction and could be reasons for this behaviour.

It should be noted that these results holds for the $[\pm 45]_s$ stacking considered in this study. Initial trials with other stacking angles indicates that the M21 material do not follow the PJN theory for all stacking sequences. This is currently under investigation in a related study.

5 Conclusions

In this study, the bias extension test method has been used to study the deformability of three different prepreg systems. The fibre rotation was followed by the use of digital image correlation (DIC). This methodology gave good, comparative results for 977-2 and M21, but not for 8552. The strain distribution was in case with 8552 was non-uniform, with areas (along the fibres) of much larger strain, which made the measurements dependent on starting point. The difference was up to 100% for one case when using the DIC. Manual measurements by the use of the freeware ImageJ® gave in that case better predictions, but in general the difference was the same for manual and DIC produced data. Given this non-uniform strain field invalidates the PJN-assumption. The very high volume fraction of fibres can be one reason for this behaviour.

By studying pictures from the tests, the evolution of deformation length scales and possible also dominating mechanisms was be detected: initially the deformation occurred seemingly continuously, but as deformation continued the deformation occurred in form of bands with no further shearing of the material inside the bands. Theory implies that intraply shear dominates during the first stage while interply friction is playing an important role in the latter. The 8552 material tested at 45°C is shown to be an exception; here no band sliding is seen, instead the intraply deformation continuous. This is probably due to its large resistant to interlaminar motion at this high viscosity.

The results show that the degree of fibre rotation could not be related to the resistance to deform. The load response from the two different material systems looked similar in its shape although differed significantly considering fibre rotation. The behaviour of the prepreg with thermoplastic particles (M21) followed the PJN-assumption while the tested 2nd generation of prepreg (977-2) differed up to 30%. Slippage seems to be the explanation to the large discrepancy for the latter material system. These results show a more predictable behaviour according to final fibre angles for M21 than 977-2, which is of great importance when calculating the final strength and shape distortions of the component.

The study also showed large difference in resistance to deformation: although having lower matrix viscosity the load response during deformation was significantly higher for the 8552 material than for the M21. This could be related to 8552 high fibre volume content and therefore less space when exposed to shear deformation. The 977-2, with a viscosity in the same range as 8552, shows a much lower resistance to deform than both the M21 and 8552. This concludes that it is not only the matrix viscosity that affects the forming behaviour.

Also, the deformation modes and their limits were shown to differ in-between the material systems. Wrinkling that was developed at approximately 25% of deformation for 977-2 and around 15% strain for 8552 could not be detected for M21. Instead, M21 weakened in-plane bonds between fibre bundles and matrix due to band sliding finally developed to in-plane splitting. It was also noted that a slower deformation rate resulted in less wrinkling for 977-2. This can be an interesting parameter when choosing forming speed for complicated shapes.

The temperature distribution during forming has been shown to be an important parameter affecting the degree of deformation. The results for M21 show that an

increased temperature gives a lower load response. A rise from 70 to 85°C lowered the load by approximately 25 %. Temperature variation, both through the thickness and in-plane, can consequently obstruct the correct forming and thereby cause wrinkles, especially in corners. A too high temperature can on the other hand lead to uncontrolled slipping and result in unpredictable fibre angles.

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Table 1. Approximate values taken from manufacturers viscosity curves.

Temperature	977-2 [Pa·s]	M21 [Pa·s]	8552 [Pa·s]
45		3000	1000
60	400	1500	400
70	120	300	180
80	50	120	75
85	30	90	45

Table 2. Experimental tests, bias extension method.

Material	Test temperature [°C]	Load speed [mm/min]
977-2 /HTA	70	10, 25, 40, 80, 100
M21/T700	70	10, 40, 100
	85	5, 10, 40, 100
	90	5, 10, 40, 100
8552/AS4	45	40
	70	40

Figure 1. Idealised figure depicting slide bands of two different widths; schematically drawn preferential speed during shear. Reduced area results in reduced preferential speed.

Figure 2. Bias extension test with idealised shear zones (PJN assumption) for $[\pm 45]$; undeformed and deformed specimen (illustration inspired by [7, 11]).

Figure 3. Unfiltered load response with filtered trace, to the left for 977-2 and the right 8552.

Figure 4. Spread of four filtered test results, 977-2 at 70°C, 40mm/min.

Figure 5. Lines between facets to measure angle rotation.

Figure 6. Bias extension test on 977-2 at four different cross-head rates and 70°C. Diamonds mark the onset of break-up of the centre line, circles mark the slide band formation and stars mark the wrinkling initiation.

Figure 7. Bias extension test on 8552, 40mm/min and at two different temperatures. Diamonds mark the onset of break-up of the centre line and stars mark the wrinkling initiation.

Figure 8. Typical large deformation splitting of M21 sample.

Figure 9. Different cross-head rates for a) 977-2 tested at 70°C, band width dependent of rate (80mm displacement) b) M21 tested 70°C, band width independent of rate (50mm displacement).

Figure 10. Load curves marked with mode transitions, for M21 at 85°C and different cross-head rates. Diamonds mark the onset of breakup of the centre line, circles mark the slide band formation and stars mark the final failure (band splitting).

Figure 11. Bias extension test on M21 at different temperatures tested at 40mm/min, errorbars representing the standard deviation of three tests.

Figure 12. Compare results different materials tested in the bias extension, all at the same temperature (70°C).

Figure 13. Fibre rotation measured at centre line, 977-2 at 70°C, compared to the theoretical PJN-rotation (including the standard deviation from four tests).

Figure 14. Fibre rotation measured at centre line, M21 at 85°C, compared to the PJN-theory.

Figure 15. Strain field after 10 mm displacement for bias extension on 8552.