FORMABILITY OF WEFT KNITTED PREFORMS

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SUMMARY: This paper investigates the formability of weft-knitted glass fiber preforms through a laboratory simulation of the deep drawing process for composite fabrication using resin transfer molding (RTM) together with a composite case study. The laboratory testing of the dry preform revealed that suitable formability parameters using a modified CBR test method could be predicted using KESF tensile properties provided that they are taken at approximately equal levels of extension. The results of the composite case study showed that there is interdependence between the mechanical properties of the dry preform, the composite shape and subsequent deformation patterns of the preform in the composite.

KEYWORDS: textiles, glass fiber, RTM, weft-knitted preforms.

INTRODUCTION

A weft-knitted preform has the potential for its mechanical properties to be tailored, due to the 3-D path of the yarns in a variety of knitted constructions. The exceptional formability properties weft-knitted preforms enable the fabrication of 3-D composite structures using RTM. The majority of reported investigations focus on the mechanical properties of the composite [1-3] and demonstrations of the shaping potential [4-6] and methods of producing sandwich fabrics using weft knitting [7]. These studies clearly indicate that weft-knitted preforms are particularly suitable for their shaping qualities. However, to the authors' knowledge, only one study on the properties of dry weft-knitted preforms, including formability concepts, has been reported [8]. Yet it has been well established that weft-knitting is an excellent candidate for forming complex shapes due to its formability properties. Knowledge of the mechanical and formability properties of the dry preform is important for a systematic engineering approach for weft-knitted preform design and subsequent composite manufacture. The authors have undertaken research into the properties of dry weft-knitted preforms and formability concepts. The initial findings [8] indicated that the formability of the weft-knit structures studied were closely related to the plain loop length component of the milano structure. This paper continues the formability investigation into the mechanical properties of preforms; full details are reported elsewhere [9, 10].

EXPERIMENTAL METHOD

Selected weft-knit preforms were manufactured using 68 x 2 tex glass fibre tows, with silane size, from Silenka Yarns on an 8-gauge (E8) Stoll ANVH/BLM-es knitting machine. The computer controlled rib-jacquard machine uses the programming language Sintral [11-12] enabling needle selection, cam setting and takedown tension setting control. The most important control features include yarn-input tension, fabric takedown tension, cam setting and speed. The preform structures investigated and reported here are full milano structures with varying physical properties (refer to Table 1). A schematic representation of the full milano structure is given in Figure 1.

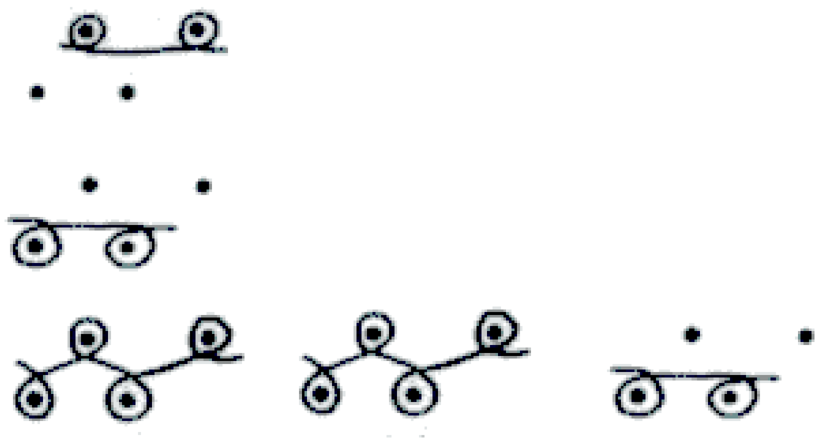

Figure 1: Full-milano, 1x1 rib and single jersey structures, respectively

The full milano structure is made up of one course of 1x1 rib and 2 courses of single jersey (one course on the front bed and one course on the back bed in order to give a balanced structure).

Table 1: Mean physical properties of full milano preforms.

Fabric	Areal density (g/sq.m)	Rib loop length (mm)	Plain loop length (mm)	Course density (c/cm)	Wale density (w/cm)
M3N	743	6.36	5.94	8.9	4.8
M32	672	6.89	5.73	8.6	4.3
M33	661.	7.80	5.53	8.9	3.9
M34	574.	8.79	5.40	8.2	3.4
M71	693.	6.14	7.49	7.8	4.6
M72	595	6.76	7.18	7.5	4.1
M73	560.	7.51	7.10	7.5	3.6
M74	557.	8.08	6.41	7.8	3.4
M9	447.	8.80	8.73	6.5	2.8
M93	513.	7.51	8.65	6.7	3.6

The mechanical properties of the dry preforms were analyzed in various mechanical test modes using the Kawabata Evaluation System for Fabrics (KESF). In textiles, this is a measurement system used for assessing the structure’s low stress mechanical and surface properties. The instruments are designed to take measurements at low stress levels whilst providing data on a wide range of parameters including deformation and recovery for each mechanical property obtained. The KESF instrumentation allows a total of 5 basic properties to be described, namely surface friction, in-plane tension, in-plane shear, transverse compression and out-of-plane bending. However the tension mode only will be discussed in this paper since it provided the best correlation with formability [9,10]. The parameters used in the analysis of the KESF tensile test are listed in Table 2.

The variables “FT” and “ET” are not standard KESF parameters for assessing the tensile behavior of fabrics. However, these parameters were devised in order to compare the tensile behavior at near the level of extension encountered during the formability (modified CBR) test method. Figure 2 gives a typical representation of the deformation/recovery curve for a weft-knitted glass fibre fabric subjected to extension in KESF testing.

Table 2: Standard parameters defined in KESF tensile testing

Variable	Property	Definition	Units
LT	Linearity of load extension curve	WT/area $Q_1Q_2Q_3$	%
WT	Energy in extending fabric to 500 gf/cm width	area Q_1 A Q_2Q_3	J/m^2
RT	Tensile resilience	area Q_1 B Q_2Q_3 /WT	%
EMT	Fabric extension at 500gf/cm width	Q_3	%
FT	Load at 15% fabric extension	FT	N/m
ET	Energy at 15% fabric extension	ET	J/m

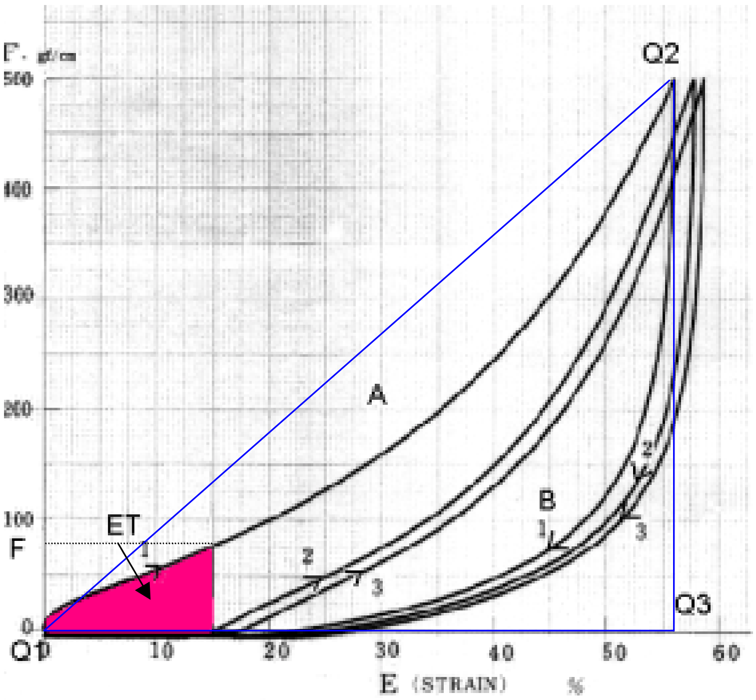

Figure 2: Typical KESF tensile deformation-recovery curve

The KESF tensile test method requires the testing of 10 specimens in the wale and course directions in specimen sizes of 20x20cm of which a 5cm gauge length is examined in the testing direction. The samples must be taken a minimum of 5cm from the fabric selvedge and sample sizes measured to an accuracy of $\pm$0.1cm. Each specimen is extended to a maximum load of 500gf/cm (i.e. 490 N/m). The load and corresponding fabric extension were recorded simultaneously in one extension and recovery curve. The KESF tensile parameters are calculated from this curve for each specimen. The principle of the tensile instrument is to measure tensile resistance under quasi plane strain conditions by extending the fabric in its principal directions (course and wale for a knitted structure).

There is no standard test method for evaluating the formability of a preform. But there is the California Bearing Ratio (CBR) plunger method for determining the burst strength of geotextiles [13]. In this test, a cylindrical plunger (46 mm diameter) is forced through the center of a circular specimen (195 mm diameter) that is gripped around its entire circumference by clamps in a loading frame. The clamping rings are located in a suitable cylinder with a minimum internal diameter of 150mm and height of 150mm. The plunger is normally lowered until it penetrates through the preform specimen. However, the plunger was lowered to a maximum displacement of 50 mm below the specimen plane to evaluate the formability (the ability to conform to a 3-D shape) of the preform. This is achieved by recording the reactive force at specified plunger displacement intervals and by measuring the energy yielded for those displacements. The two parameters found suitable as formability measures are the formability energy (FCE5) and the formability load (FCL5) for a cylindrical plunger at the 50 mm displacement level. Figure 3 shows a photographic image of the general arrangement used in the CBR test method.

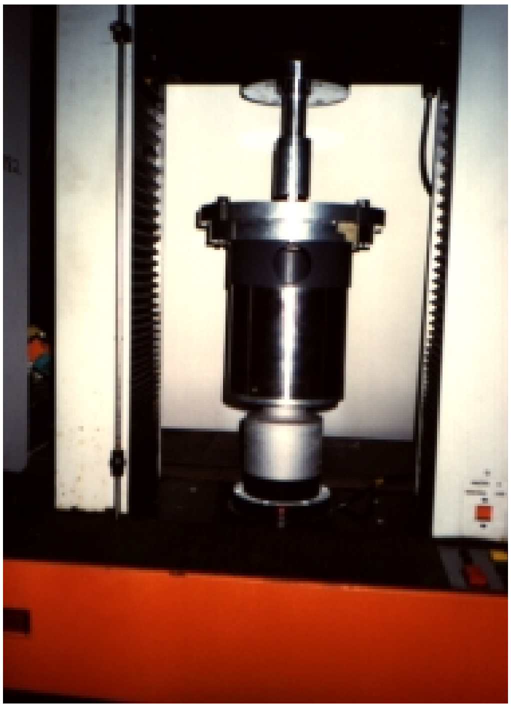

Figure 3: Picture of the CBR test method.

Regression analysis techniques were used to evaluate the relationships between the KESF parameters and the CBR formability measures. However, the large number of standard KESF parameters were reduced by eliminating hysteresis parameters as being irrelevant to the CBR formability test (i.e. recovery cycle not considered). In addition, the new KESF tensile parameters (Table 2) were introduced after consideration of simple geometric models for fabric extension in the formability test: maximum fabric extension with and without the inclusion of friction was calculated at 39% and 27%, respectively. The level of extension used as the base for determining the tensile force (FT) and energy (ET) parameters does not necessarily need to correspond to these extension levels. However, it is desirable that the designated extension level be achievable by all preforms and that an approximate linearity be evident in the tensile loading curve at that extension level. This was the basis for selection of 15% extension in the definition of the tensile force and energy parameters (Table 2).

The modified CBR test method is basically a laboratory simulation of the deep drawing process employed during RTM. The plunger employed in the CBR test method for assessing the formability of the preform is geometrically symmetrical. However this is not always the case with actual industrial applications. Therefore, in order to assess the formability of an asymmetric shape and to relate the findings of the specific preforms manufactured to subsequent composites, a composite case study was also investigated. Figure 4 provides a view of the composite component investigated – a helicopter door track pocket.

Figure 4: Actual picture of composite component.

Due to the use of a relatively transparent resin (redux 501), the contrast between the preform and epoxy in the composite enabled visual analysis of the deformed preform after processing. The analysis of deformation patterns of the preforms in its composite form was achieved by the use of photographic images of the deformed preforms. In Geographic Information Systems (GIS), the map is typically defined by outlining the boundaries of a polygon or unit area [14]. The technique used here involved the transformation of the photographic images into a less detailed map consisting only of an outline of the photographic image and grids of 10 courses x 5 wales. The photographic image for a milano preform is shown in Figure 5 and the map for the same sample is given in Figure 6.

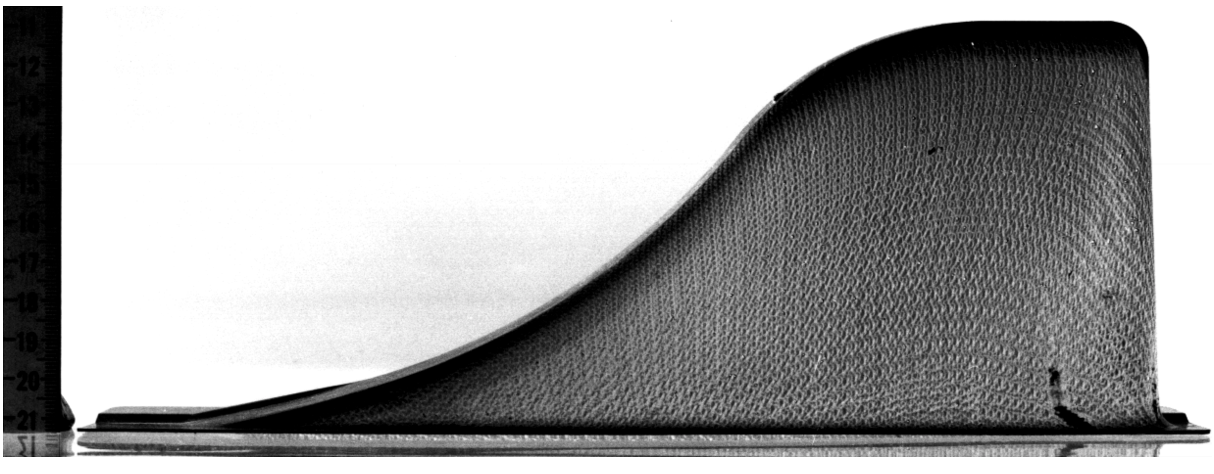

Figure 5: Photographic image of milano knit reinforced composite.

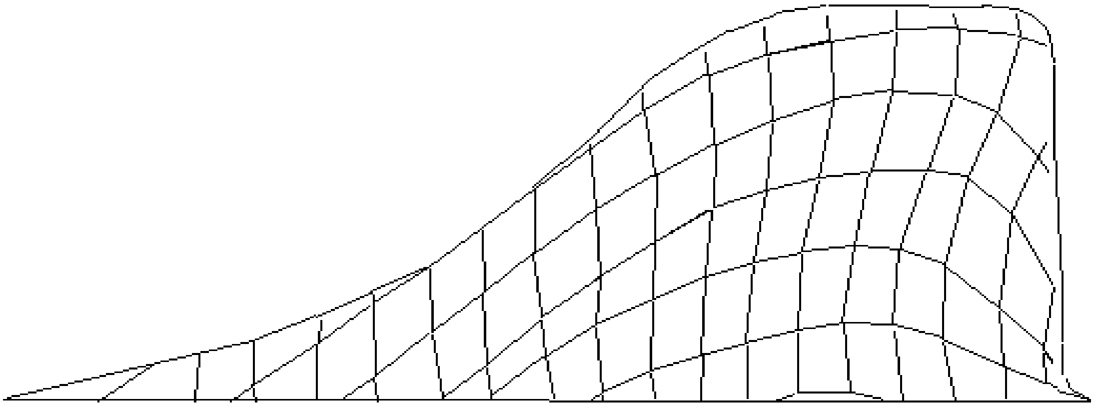

Figure 6: Map of milano knit reinforced composite image in Figure 5

The mapping technique used to convert the tracings into computer readable coordinates was based on measurement of each marked grid (i.e. 5 wales x 10 courses). Original wale and course spacing is known for the flat preforms. The wale and course spacing after processing the preforms into the composite was determined through the tracings derived from the photographic images of each panel. Each grid was assigned with (x, y) coordinates at its centroid. Various strain/deformation fields were then calculated, including course and wale elongations, shear angles, and stitch areal deformation. The latter was based on the area of the polygon grid consisting of two triangles (refer to Figure 7) as shown in Equation 1.

Equation 1: *Stitch areal deformation*

$$= \frac{\text{(stitch density of flat preform – stitch density of deformed preform)}}{\text{stitch density of flat preform}}$$

$$= \frac{\{0.5\, a\, c \sin\theta_1 + 0.5\, b\, d \sin\theta_2 - (50/wc)\}}{(50/wc)}$$

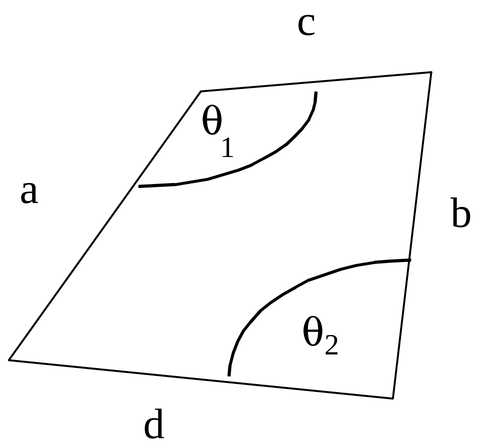

Figure 7: Representation of polygon with relevant sides and angles.

Although some polygons were irregular shapes, the size of the polygons taken was sufficiently small to neglect errors related to the path of their boundaries. Each structure was replicated 3 times and the resulting deformation measurements are representative of the full sampling.

RESULTS OF THE DRY PREFORM STUDY

Although knowledge of formability is a useful tool for deep drawing, it is not a standard test method. Therefore the ability to predict formability from a common mechanical property such as tensile behaviour is of practical significance. Table 3 provides a summary of the regressions [9, 10] of KESF parameters on the formability energy (FCE5) and the formability load (FCL5).

Table 3: Summary of weighted regression analysis between formability and mechanical properties

KESF Tensile parameters	R^2	
	FCE5	FCL5
EMTC	.52	.52
EMTW	.83	.78
WTC	.04	.04
WTW	.05	.06
LTC	.62	.61
LTW	.75	.74
FTC	.91	.91
FTW	.87	.90
ETC	.92	.94
ETW	.85	.86

Table 3 indicates a very high correlation between the tensile force in the course direction (FTC) required to extend the fabric 15% and formability. The results strongly suggest that both the tensile energy (ETC) and load (FTC) to extend the fabric to 15% correlate with the formability of the fabric to the level of extension previously outlined. The findings also show that the course direction in the mechanical properties provides a better prediction of formability than the wale direction. The relationship between the specified tensile energy (ETC) and formability (FCE5) for the cylinder is shown in Figure 8.

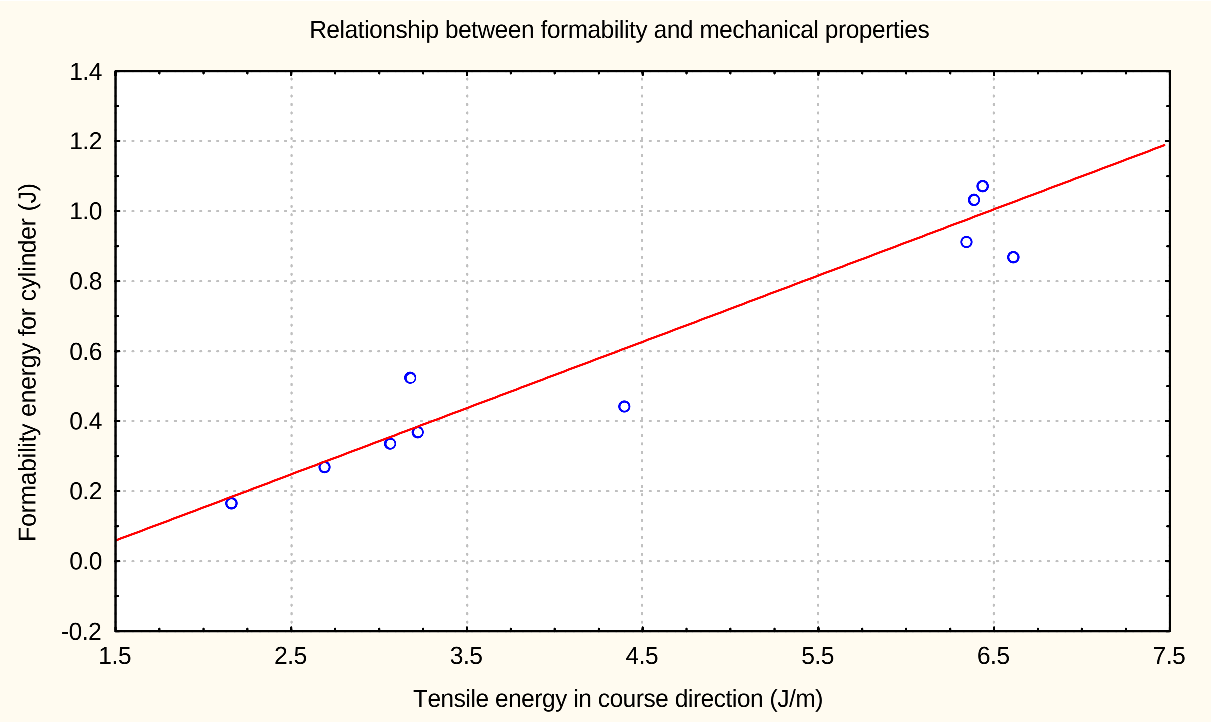

Figure 8: Relationship between cylinder formability energy and tensile energy

The results show that an increase in the tensile load or energy corresponds to an increase in the formability energy and in the formability load. This means that if a larger force is required to deform the fabric in the tensile mode, the larger is the force to deform a fabric during deep drawing. In fact, the findings indicate with a high degree of confidence that the tensile properties alone may be used to predict the formability of a full milano fabric.

RESULTS OF THE COMPOSITE CASE STUDY

The composite case study involved the fabrication of weft-knitted glass-fibre epoxy structures. The manufactured composite is an asymmetric component, which requires a high degree of preform deformation, thus making it difficult to fabricate. Figure 9 gives an example of a contour graph indicating the distribution of the preform areal deformation in the composite case study derived from photographic images of the composite. As can be seen in the figure, the apex of the component is associated with high stitch deformation (low stitch density) whereas the left and right base positions have relatively low stitch deformation. Clearly, the insitu fibre volume fraction varies throughout this composite component.

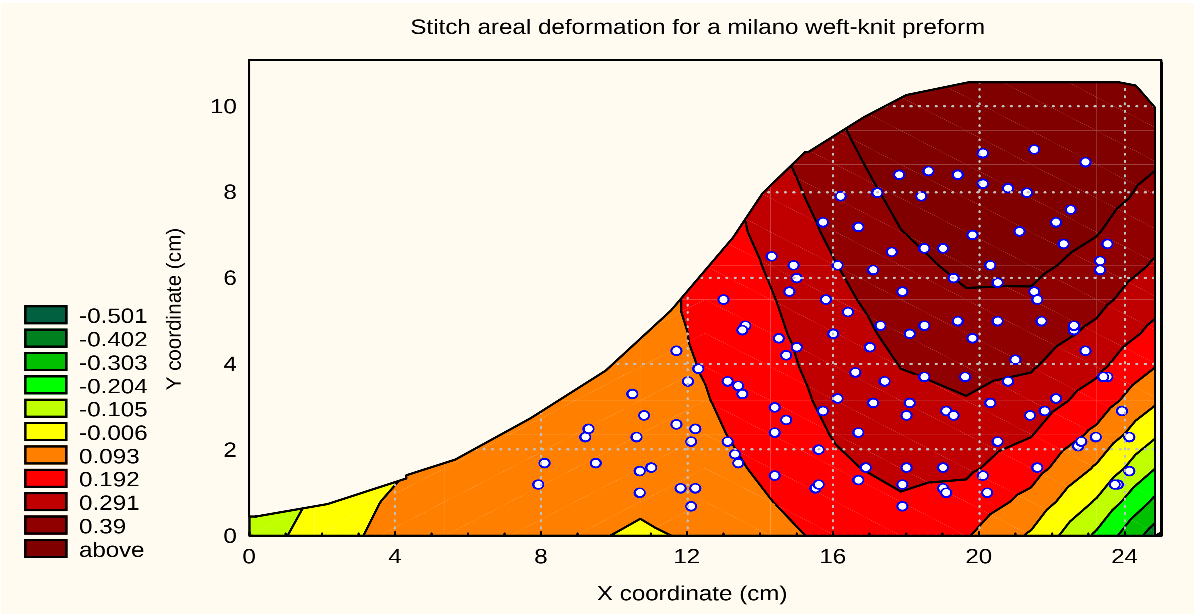

Figure 9: Stitch areal deformation for a milano weft-knit preform.

Faults in subsequent composites are a significant indication of poor formability. For instance, an excessive degree of extension of the preform can result in holes in the composite. Although the lateral compressive force exerted by the mould itself may also contribute to this type of fault, the tensile loads applied by stretching during the deep drawing process undoubtedly influence such faults and the knit material “flow”. Deformation of the preforms basically occurs through redistribution of the principal directions of the knit structure. In the case of fibre/loop failure, adjacent intact fibres/loops can no longer support any tension thus resulting in a hole as shown in Figure 10. A by-product of holes in the composite, particularly when the hole is sufficiently large, is cracking. Cracking usually occurs during removal of the composite from the mold because of the absence of the preform in this region. The resultant regions containing only resin in effect become the weakest points in the composite, thus being prone to cracking.

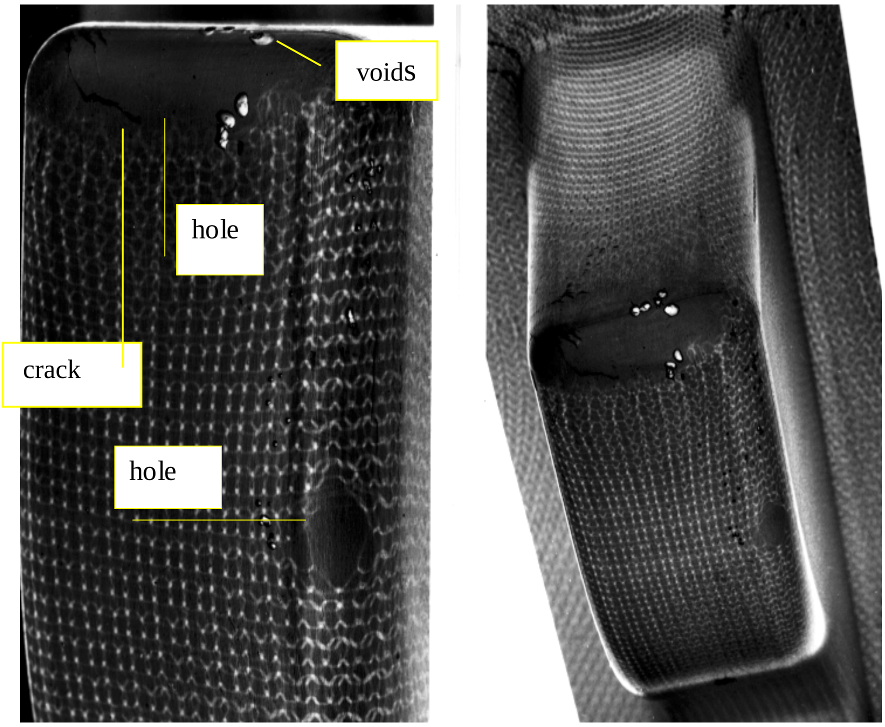

Figure 10: Photographic images of faults in the composite with a glass fibre milano preform.

The results of the composite case study have shown that formability for a given industrial application is not only a function of the dry preform properties measured in tension and in the modified CBR test method but also of the relative distribution of the preform in the composite part. The latter is influenced by the mold design, the cutting pattern applied to the dry flat preform and operator handling during the deep-drawing process. The results showed that the degree of faults and the distribution of the preform elongation in the composite influence formability. The investigation highlighted the importance of the application of the preform, emphasizing the impact that preform evenness and faults play in defining formability as well as the deep drawing of preforms in the RTM process.

CONCLUSION

The formability of the dry weft-knit preforms was investigated in relation to their mechanical properties. The findings provide a means of predicting the formability of weft-knitted preforms prior to manufacture of the composite through specific tensile properties. The definition of formability is enhanced by the case study of weft-knitted glass reinforced composite structures emphasizing the interdependence of the mechanical properties of the preform, the mould design and the RTM operating procedures. Therefore this research clearly establishes the need for an engineering database for weft-knitted preforms used in deep drawing applications.

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REFERENCES

1. Ramakrishna S., Cuong N.K. and Hamada H. (1997), "Tensile properties of plain weft knitted glass fibre fabric reinforced epoxy composites", Journal of reinforced plastics and composites, vol. 16, no. 10, 946-966.

2. Ramakrishna S. and Maekawa Z. (1997), "Characterization and Modeling of Tensile properties of plain weft knitted fabric reinforced composites", Composites Science and Technology, vol. 57, 1-22.

3. Ruan X. and Chou T.W. (1998), "Failure behaviour of knitted fabric composites", Journal of Composite Materials, vol. 32, no. 3, 198-221.

4. Mayer J., Wintermantel E., DeAngelis F., Niedermeier M., Buck A. and Flemming M. (1991), "Carbon fibre knitting reinforcement of thermoplastics: A novel composite", Proceedings of 2nd European conference on advanced materials and processes, London, July 22-24, vol. 2, 18-26.

5. Mayer J., Ha S.W., Ruffiex K., Tognin R., Kock B. and Wintermantel E. (1994), "Knitted Fibre Reinforced Composites", Automotive Engineering, August, 21-24.

6. Ruffieux K., Hintermann M., Mayer J., Koch B. and Wintermantel E. (1992), "Enhanced local carbon fibre knitting reinforcement of mechanical adapted bone plates. Concept of a new implant", Textiles and Composites, June, 326-331.

7. Hong H, de Araujo M. and Fangueiro R. (1996), "3-D technical fabrics", Knitting International, no. 1232, 55-57.

8. S. Savci and J.I. Curiskis (1997), "Weft-knitted glass-fibre preforms for composite materials", ICCM 11, Australia, 14-18 July, vol. 5, 338-348.

9. S. Savci (1998), "Formability of weft-knitted preforms", Ph.D. Thesis, UNSW.

10. S. Savci, J.I. Curiskis and M.T. Pailthorpe (submitted for publication), "A study of the formability of weft-knitted preforms for advanced composite structures: parts I-IV".

11. Stoll, ANVH-BLMES Operating Manual.

12. Raz S. (1991), "Flat knitting: the new generation", Bramberg, Meisebach.

13. AS3706.4 (1990), "Method 4: determination of burst strength – California Bearing Ratio Plunger Method", Geotextiles – Methods of Test, Standards Australia.

14. Langston R.D. (1982), "Creating your own SAS/graph map data sets with a digitiser", SAS Technical Report A-107, SAS Institute Inc, U.S.A.