Study on parameters affecting the mechanical properties of dry fiber bundles during continuous composite manufacturing processes

A Maier[1] and R Schledjewski[1, 2]

[1]Processing of Composites, Department Polymer Engineering and Science, Montanuniversitaet Leoben, Otto-Gloeckel Straße 2, A-8700 Leoben, Austria

[2]Corresponding author: ralf.schledjewski@unileoben.ac.at
Phone: +43 3842 402 2700, Web page: http://www.kunststofftechnik.at/composites/

Abstract. For continuous manufacturing processes mechanical preloading of the fibers occurs during the delivery of the fibers from the spool creel to the actual manufacturing process step. Moreover preloading of the dry roving bundles might be mandatory, e.g. during winding, to be able to produce high quality components. On the one hand too high tensile loads within dry roving bundles might result in a catastrophic failure and on the other hand the part produced under too low pre-tension might have low quality and mechanical properties. In this work, load conditions influencing mechanical properties of dry glass fiber bundles during continuous composite manufacturing processes were analyzed. Load conditions, i.e. fiber delivery speed, necessary pre-tension and other effects of the delivery system during continuous fiber winding, were chosen in process typical ranges. First, the strain rate dependency under static tensile load conditions was investigated. Furthermore different free gauge lengths up to 1.2 m, interactions between fiber points of contact regarding influence of sizing as well as impregnation were tested and the effect of twisting on the mechanical behavior of dry glass fiber bundles during the fiber delivery was studied.

1. Introduction

Composites are used in high amounts in different fields of application such as automotive, aerospace, marine, buildings, civil infrastructure, and sporting. High performance mechanical properties in combination with low weight are most often the reason to use composite materials. Although carbon fibers deliver best performance, glass fibers (GF) are due to lower prices the most widely used reinforcement in polymer matrix composites (PMCs). Glass fibers and glass fiber-reinforced plastics appear to behave as brittle materials. Already 1920 Griffith introduced the concept that glass contains pre-existing flaws, so that the fracture process is one of crack propagation rather than crack initiation. Weibull extended this concept by reasoning that the flaws are randomly distributed throughout the body and are of random severity. The "weakest-link" approach was adopted as a criterion of failure or a brittle material fails when the stress at any one flaw becomes larger than the ability of the surrounding material to resist the local stresses. Applying the statistical laws of probability, Weibull assumed a reasonable distribution function and derived an according expression [1,2,3].

In composite manufacturing processes the dry, i.e. not impregnated fibers are delivered, e.g. from a spool creel, to the point where the final component is formed. So, the dry fibers have to withstand tensile and bending forces due to friction, when in contact with guiding elements, or break systems, installed to receive defined pre-tensioning of the roving. For process optimization a good understanding about dry roving behavior is necessary. Therefore free gauge lengths of glass fiber bundles in dimensions relevant for continuous manufacturing processes in combination with influencing factors such as sizing, impregnation and shear stresses and strains on the maximum tensile loads of glass fibers were investigated in detail in this work.

2. Theoretical Background

2.1. Length effect

Based on the theory of the statistical probabilities for critical voids within the tested volume the tensile strength or the maximum tensile load is linked directly to the statistical failure probability, which in consequence means that the theoretical strength is the ideal strength and based on the increasing test volume (from short single fiber to bulk material) a decreasing strength will occur. The chance of the presence of a critical void inside a tested volume is increasing when the test volume is increasing. The amount of voids or defects, their shape and their distribution inside the test volumes are based on several facts as for example the manufacturing process of the test samples or the type of material itself but are in every tested volume statistically identical. Therefore the theory of the statistical failure distribution is only addressing the presence of one critical defect. That one critical defect leads, based on its higher stress concentration caused by the shape of the void in combination with the void size and position inside test volume, to a higher local stress σ_{local} than the global stress $\sigma_{nominal}$ and with a reduced cross section to an earlier catastrophic failure at lower applied forces F [1,2,3,4,5,6].

2.2. Interaction points

The interaction between single filaments within a fiber bundle and between fiber bundles is always a contact point between the fiber sizing. Therefore the interaction behavior is based on the mechanical and chemical interactions between the types of sizing.

The main purpose for sizing and finisher is to act as both protection of the raw glass fibers and bonding the organic functional groups to the matrix. These functional groups (R) have to assure chemical compatibility with the later used matrix resin [7,8,9]. Silane coupling agents are especially developed for glass fiber surfaces and drastically improve the bonding between glass fibers and epoxy matrices. Furthermore silane groups are perfectly protecting the raw glass fibers against water absorption. Therefore the coupling agents are performing a chemical bond between the glass fiber and the polymerized silane in a multilayer structure [10,11].

2.2.1. Friction. The friction force F_f, which is the fundamental characteristic of friction of two surfaces, is determined by the interaction of the two surfaces, whose real contact area will be denoted by S. Usually, the friction force is a function of the pressure p, the sliding velocity v, the temperature T, the contact time, and other external friction parameters [12,13]. According to prevailing ideas, the friction force can be divided, as shown in equation 1:

$$F_f = F_a + F_d \quad (1)$$

Where F_a is the adhesion component, which is based on the van der Waals interaction between the friction members, and F_d is the deformation component, which is associated in particular with the deformation of asperities induced in the counter body by the harder member of the friction pair [12,13].

2.3. Twisting

Whether using yarns, characterized by a slight twist when delivered, or using rovings, with an inside payout from the bobbin, more or less pronounced twist will result in compaction and shear effects between the filaments. Due to the fact that experimental shear tests are only possible for UD fiber-matrix laminates by using the indirect route via in-plane shear tests, one can imagine that testing the shear behavior of dry fiber rovings, which are not fixed into a matrix system, is even more complex and standardized tests are not available. The experimental testing of shear stress - shear strain behavior of composite laminates can become rather complex. For multi-directional fiber lay-ups and woven or braided fabrics, the V-notched rail shear test is a very common testing method [14]. However, this test cannot be recommended for measuring the shear stress-shear strain behavior of unidirectional laminates because the measured results are not reliable [14]. This results mainly from the fact that, depending on the position of the UD laminate within the testing device, either the matrix or the fibers are highly loaded by shear which is not representative for the shear behavior of the entire laminate. In order to be able to measure the shear stresses and strains of UD laminates nevertheless, the so called "in-plane shear test" can be used [15]. The test's name results from the test procedure, where the UD fibers are arranged under ±45° in a laminate and not a real shear load, but a tensile load is applied during the experimental test. The angle between the tensile load (0°) and the ±45° results in a stress state within the laminate similar to a shear test.

To analyze the effect of twisting/shear on dry glass fibers under tension the tests under twisting were conducted under close circumstances to the "in-plane shear test".

3. Materials and Sample Preparation

3.1. Materials

Glass fiber rovings used are standard StarRov® 086 4800tex E-glass fiber rovings from Johns Manville (Denver, United States) [16].The diameter of each filament was approximately 23 µm according to the manufacturer data sheet. A typical epoxy resin system was used to study the effect of impregnation. EPIKOTE^{TM} Resin MGS LR 160 and EPIKURE^{TM} Curing Agent MGS LH 502 by Hexion Specialty Chemicals B.V. (Rotterdam, Hoogvliet, Netherlands) were used.

3.2. Roving bundle sample preparation

To ensure a consistent load introduction into the specimens and an equal strain behavior of the roving, the specimens had to be prepared before inserting them into the tensile testing rig (Figure 1). This was done by using two-component epoxy glue and roughened aluminum tabs. To ensure that all single filaments were glued together low viscosity glue was used. To ensure that the applied test forces will be held by the epoxy matrix a special treatment was applied. During the bonding process a pressure of 1.5 bar and a temperature of 100 °C were applied for 100 seconds. Due to that process a bonding force of 2500 N/cm² was reached based on the two component epoxy data sheet. Specimens with free testing length between the plates of 50 mm, 150 mm, 300 mm, 500 mm, 800 mm, 1000 mm, and 1200 mm were produced.

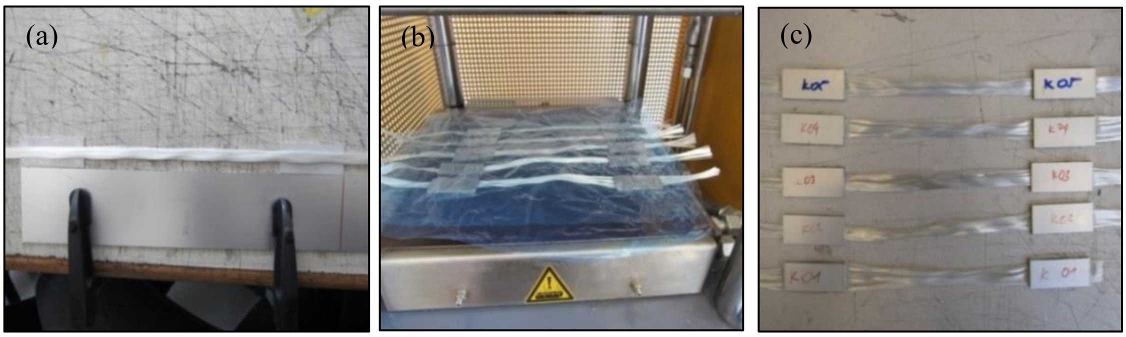

Figure 1. (a) Aligned E-glass roving and aluminum tabs (b) special tabs treatment with heat and pressure (c) resulting testing samples.

4. Experimental results

4.1. Effect of the strain rate on the mechanical properties

The strain rate dependency can be interpreted as a nearly linear increase of the maximum tensile load with an increasing strain rate as expected from the literature [17,18,19]. Based on preliminary tests and the information of the effect of strain rate dependency on the tensile load found in literature, a strain rate of $6*10^{-3}$ s^{-1} was chosen for all tests presented in this paper. This decision was affected mainly by the possible and controllable parameters given by the tensile test machines.

4.2. Effect of free gauge length on the mechanical properties

In Figure 2 the effect of different free gauge lengths on the maximum tensile loads and in consequence the survivability based on the statistically failure distribution of the rovings tested is shown in detail. Included in this figure are the measured data from 50 mm up to 1200 mm free gauge length, which is a scale reasonable to represent the fiber delivery in continuous manufacturing processes. Figure 2 clearly shows that with an increasing free gauge length the maximum tensile load decreases. Even at the very long specimens with more than 1000 mm free gauge length, this trend continues. The top of Figure 2 indicates a 100 % survivability of the fiber bundle which means that during all of the tests no fatal fiber failure was detected.

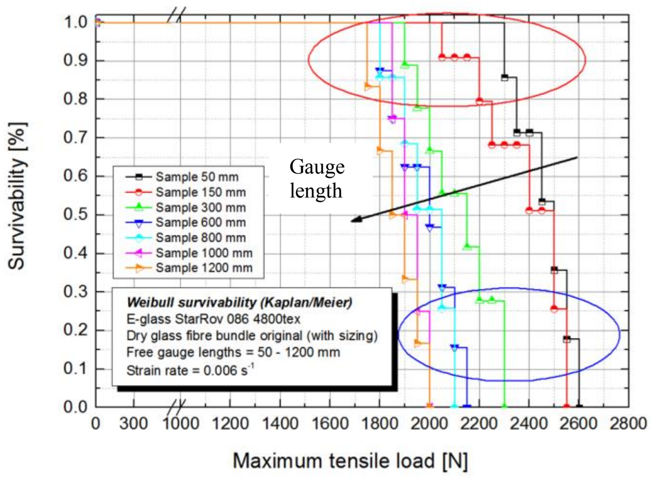

Figure 2. Survivability and maximum tensile load as a function of free sample length.

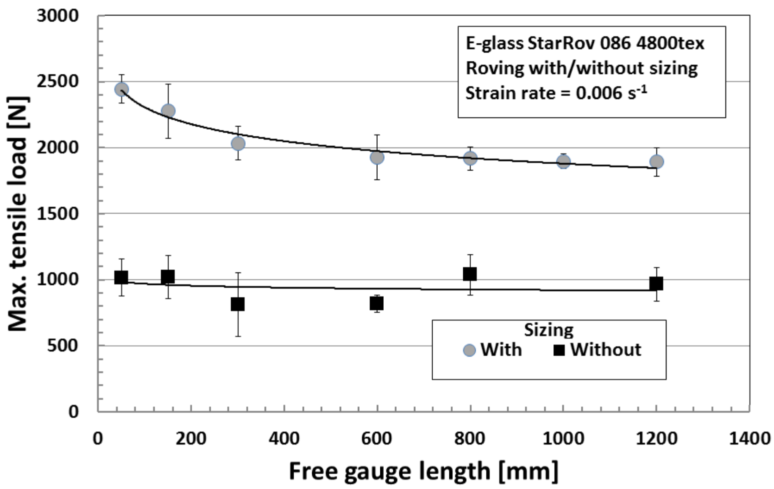

Figure 3. Comparison of glass fiber with and without sizing.

4.3. Effect of sizing

In order to investigate the effect of sizing, the sizing on the fibers as delivered was chemically removed by using piranha solution. Piranha solution acts on organic materials and it is expected any fiber sizing, finish or any other surface treatment done during fiber manufacturing is removed. The glass fiber itself is expected to be inert during such a treatment. Both, fibers as delivered and without sizing, were mechanically tested with different gauge length. The load-strain curves of the chemical treated fibers (without sizing) clearly showed that the missing sizing resulted in a decreased maximum tensile load from approximately 2000 N to less than 1000 N (Figure 3). An explanation for this effect is a more pronounced adhesive interaction of sized glass fiber surfaces compared to the glass fiber surfaces without sizing. Due to friction such adhesive interaction results in a failure behavior of the roving quite comparable to a composite material. The sizing acts here like a matrix and in case of failure of single filaments in the roving the load transfer into surrounding placed filaments is given.

4.4. Effect of twisting on the mechanical properties

During the tests to analyze the influence of twisting an interesting trend was found, showing that the maximum tensile load first increase when low twist is given and later on decrease with an increasing number of twists (Figure 4).

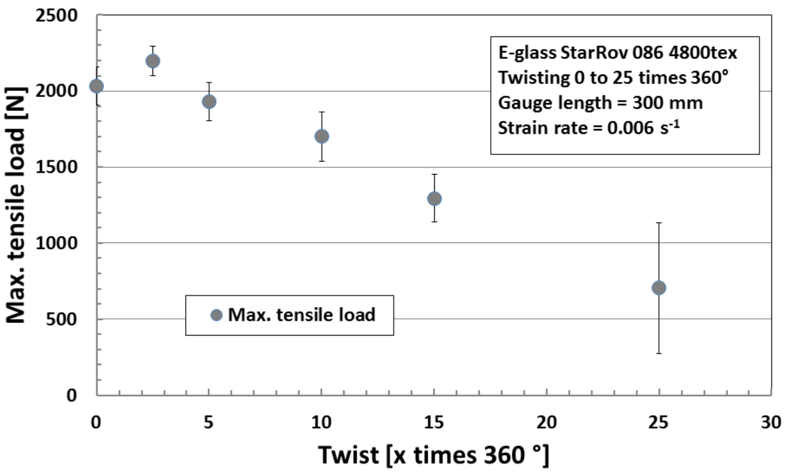

Figure 4. Analysis of the maximum tensile load with standard deviation over number of twist.

The increasing load capability is explained by a compaction of the fiber bundle in the twisted zone. Due to the compaction the adhesive inter-filament load transfer mechanisms are intensified. An increased tolerance against single filament failure due to load transfer into surrounding filaments leads to an increased maximum tensile load during testing. Since the rovings have been fixed by the aluminum tabs before twisting and the roving was glued having a distinct width, filaments located in maximum distance to the rotation axis during twisting will reduce the distance between the end-tabs (Figure 5). Consequently, filaments located more close to the rotation axis will contribute to load bearing during tensile test earliest when an according elongation of the specimen is given. Tensile testing of twisted rovings, as it has been done in this study, results in a stepwise filament load bearing and filament failure which results in an increase of elongation before final fatal failure of the roving (Figure 5). Due to this failure behavior only a part of the filaments is under load and these filaments do reach their maximum load capability already before further filaments do contribute to load bearing. The stiffness of highly twisted samples is significantly lower and the final maximum load reached during testing is significantly lower (Figure 5).

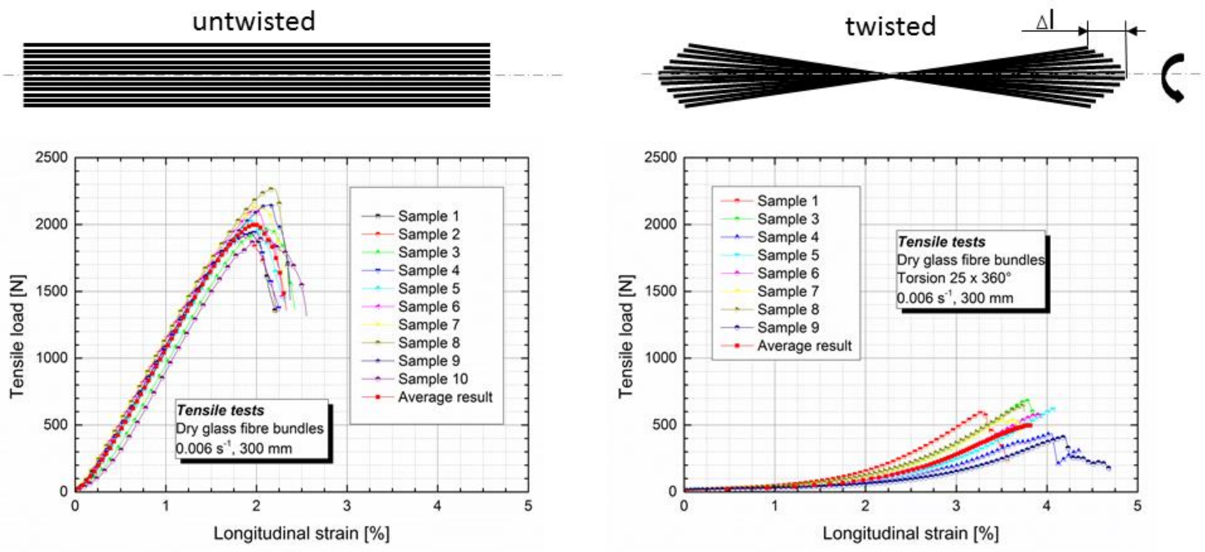

Figure 5. Effect of twist on failure behavior during tensile testing.

4.5. Effect of impregnation

Since the inter-filament load transfer is already identified to govern the failure behavior under tensile load a further comparison was made by using resin impregnated rovings. The resin impregnation was done directly before doing mechanical testing. No resin curing effects are assumed to affect the experimental results. Compared to the dry fiber bundles the impregnated ones result in significantly higher maximum tensile load (Figure 6). These results are quite in line with the results elaborated before (Figure 7). The ability to transfer the mechanical load from one filament to surrounding ones reduces the brittle failure behavior of the fiber bundles. Dry fibers without any surfaces covers (sizing) do only have distinct point contacts having only low adhesion effects. If the filaments are covered by polymeric sizing material, the adhesion improves and load transfer mechanisms are enhanced. Low roving twist results in higher compaction and as a result more pronounced intimate contact and further enhanced inter-filament load transfer is given. Further improvement is reached by impregnation. The resin will enhance the load transfer especially in the region of no direct contact between the filaments. Additionally, the resin might support relocation of the fiber position due to lubrication effects. This could result in more direct contact points or even line contact between the filaments.

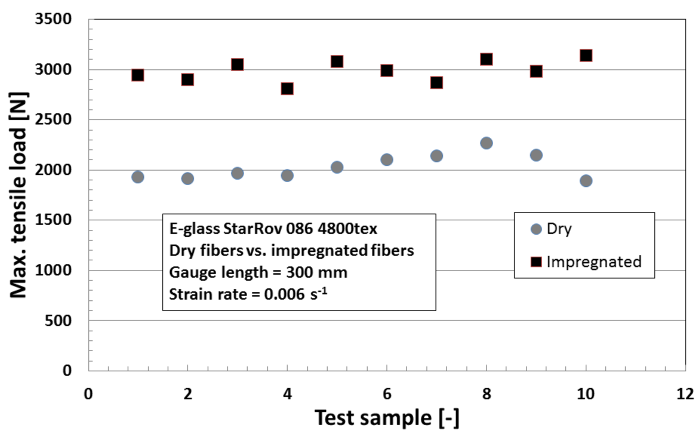

Figure 6. Maximum tensile load for dry and resin impregnated fiber bundles.

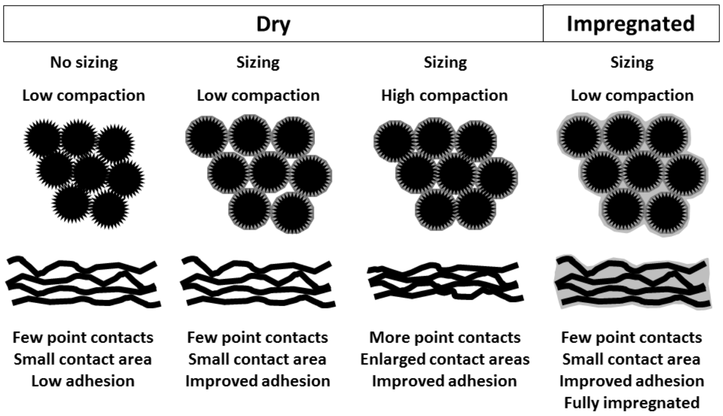

Figure 7. Effects of the variation of load transfer conditions

5. Conclusion

During fiber delivery in continuously running processes several different effects might become relevant. The load bearing behavior of the fiber bundles is influenced by (a) the inter-filament adhesion, (b) the compaction of the fiber bundle, (c) the amount and shape of interaction areas, (d) the free length the load is acting, and (e) whether the fiber bundle is already impregnated, or not.

The resulting maximum (tensile) load the roving can withstand varies in a wide range. For most processing configurations the fiber tension typically do not reach the shown limits, exemplarily elaborated for one roving grade in this paper. In some cases, e.g. if pre-tensioning during winding is given, these limits have to be known very well to ensure save fiber delivery. As shown by the results presented, in the configuration delivering the maximum tensile loads, i.e. impregnated fibers, the maximum tensile load of about 3000 N is equivalent to a tensile strength of about 1500 MPa if all filaments are similar loaded. This is less than half the level of typical tensile strength known for e-glass!

References

[1] Griffith A A 1920 *The phenomena of rupture and flow in solids (Philosophical transactions / Royal Society of London* ser. A, v. 221*)* (London)
[2] Weibull W 1939 A Statistical Theory of the Strength of Materials *Ceneralstabens Litografiska Anstalts Förlag* **1939**
[3] Lund M D 2010 Tensile Strength of Glass fibres *Dissertation* Section of Chemistry Department of Biotechnology, Chemistry and Environmental Engineering, Aalborg University
[4] Soric Z, Galic J and Rukavina T 2008 Determination of tensile strength of glass fiber straps *Mater Struct* **41** 879
[5] Andersons J, Joffe R, Hojo M and Ochiai S 2002 Glass fibre strength distribution determined by common experimental methods *Composites Science and Technology* **62** 131
[6] Neuber H 1985 *Kerbspannungslehre: Theorie der Spannungskonzentration ; genaue Berechnung der Festigkeit* 3rd edn (Berlin: Springer)
[7] Campbell F C 2010 *Structural composite materials* (Materials Park, Ohio: ASM International)
[8] Brown E N, Davis A K, Jonnalagadda K D and Sottos N R 2005 Effect of surface treatment on the hydrolytic stability of E-glass fiber bundle tensile strength *Composites Science and Technology* **65** 129
[9] Jones F R 1996 Interphase Formation and Control in Fibre Composite Materials *KEM* **116-117** 41
[10] Feuillade V, Bergeret A, Quantin J-C and Crespy A 2006 Relationships between the glass fibre sizing composition and the surface quality of sheet moulding compounds (SMC) body panels *Composites Science and Technology* **66** 115

[11] Feuillade V, Bergeret A, Quantin J-C and Crespy A 2006 Characterisation of glass fibres used in automotive industry for SMC body panels *Composites Part A: Applied Science and Manufacturing* **37** 1536–44
[12] Uetz H and Wiedemeyer J op. 1985 *Tribologie der Polymere: Grundlagen und Anwendung in der Technik: Reibung, Verschleiss, Schmierung* (München, Wien: Carl Hanser)
[13] Bartenev G M, Lavrent′ev V V, Lee L-H and Ludema K C 1981 *Friction and wear of polymers (Tribology series* v. 6*)* (Amsterdam, New York, New York: Elsevier Scientific Pub. Co.; Distributors for the U.S. and Canada, Elsevier/North-Holland)
[14] ASTM International 2005 Standard Test Method for Shear Properties of Composite Materials by V-Notched Rail Shear Method *(*ASTM D7078/D7078M-05*)* (West Conshohocken, PA, United States: ASTM International)
[15] ASTM International 2007 Standard Test Method for In-Plane Shear Response of Polymer Matrix Composite Materials by Tensile Test of a ±45° Laminate *(*ASTM D3518/D3518M-94*)* (West Conshohocken, PA, United States: ASTM International)
[16] JohnsManville StarRov: Direct Roving 086 (accessed 7 Dec 2015)
[17] Barré S, Chotard T and Benzeggagh M L 1996 Comparative study of strain rate effects on mechanical properties of glass fibre-reinforced thermoset matrix composite *Composites Part A: Applied Science and Manufacturing* **27** 1169–81
[18] Arao Y, Taniguchi N, Nishiwaki T, Hirayama N and Kawada H 2012 Strain-rate dependence of the tensile strength of glass fibers *J Mater Sci* **47** 4895–903
[19] Elanchezhian C, Ramnath B V and Hemalatha J 2014 Mechanical Behaviour of Glass and Carbon Fibre Reinforced Composites at Varying Strain Rates and Temperatures *3rd International Conference on Materials Processing and Characterisation (ICMPC 2014)* **6** 1405–18