"Siphon impregnation": The development of a new method for impregnation during filament winding

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SUMMARY

A new impregnation system for the wet out of rovings during the filament winding has been developed. The siphon is a close type impregnation system without any moving parts. Experiments show good impregnation quality, low resin waste, and longer run times in comparison with open bath systems.

Keywords: Filament winding, impregnation, pressure vessels

INTRODUCTION

Composite materials and filament winding is one of the most competitive technology combinations for the production of pressure vessels and convex geometries [1]. Over the last years the demand for high end pressure vessels is constantly rising due to the development of the hydrogen technology. A key feature for the success of the technology is the improvement of the manufacturing procedure.

The main industrially available impregnation method for the filament winding is the impregnation of the fibers in an open bath. One of the main drawbacks of the open bath is that the resin viscosity, which changes over time and temperature, affects the impregnation quality. Moreover the system cannot generally be adjusted while the fibers are being drawn over the impregnation roller. A further and important disadvantage is that a large areal surface of resin is exposed to the air which will cause advancement for the moisture sensitive resins [2].

Over the last years efforts have been taken in order to replace the open bath impregnation systems with new close type designs [3,4]. The impregnation of the travelling fiber pack can be carried out in 2 ways. The first one is to guide the roving though a die which will compact the fibers and to inject the resin under high pressure. The main disadvantage of the "high pressure" designs is the resin backflow and the fibers' abrasion caused by the high compaction rate of the fibers. On the contrary the "low pressure" designs try to enchase the impregnation by applying a low hydrostatic pressure on the resin and wetting the fiber bed due to the act of capillary pressure. During the impregnation process the roving has to be spread out, a pressure has to build up on the resin in the gap between roving and die wall, and the resin has to penetrate the fiber bed due to the hydrostatic force and the capillary forces.

Institute für Verbundwerkstoffe (IVW) has developed the "Siphon impregnation system" which is a close type, low pressure impregnation system for the filament winding process. The impregnation occurs as single carbon fiber rovings running through a curved path while the resin is injected in the entry [5].

IMPREGNATION MECHANICS INSIDE THE SIPHON

As it can be seen in Figure 1, the siphon consists of a curved path where a single roving runs under a constant speed and resin is dosed under a constant rate. The roving slides over the curved surface of the siphon and a thin resin film is created between roving and siphon surface. The thickness of this film δ depends on the process speed U, the resin viscosity η, the roving width W, and the roving tension T [6].

$$\delta = 1.4\left(\frac{U\eta W}{T}\right)^{2/3} \quad [1]$$

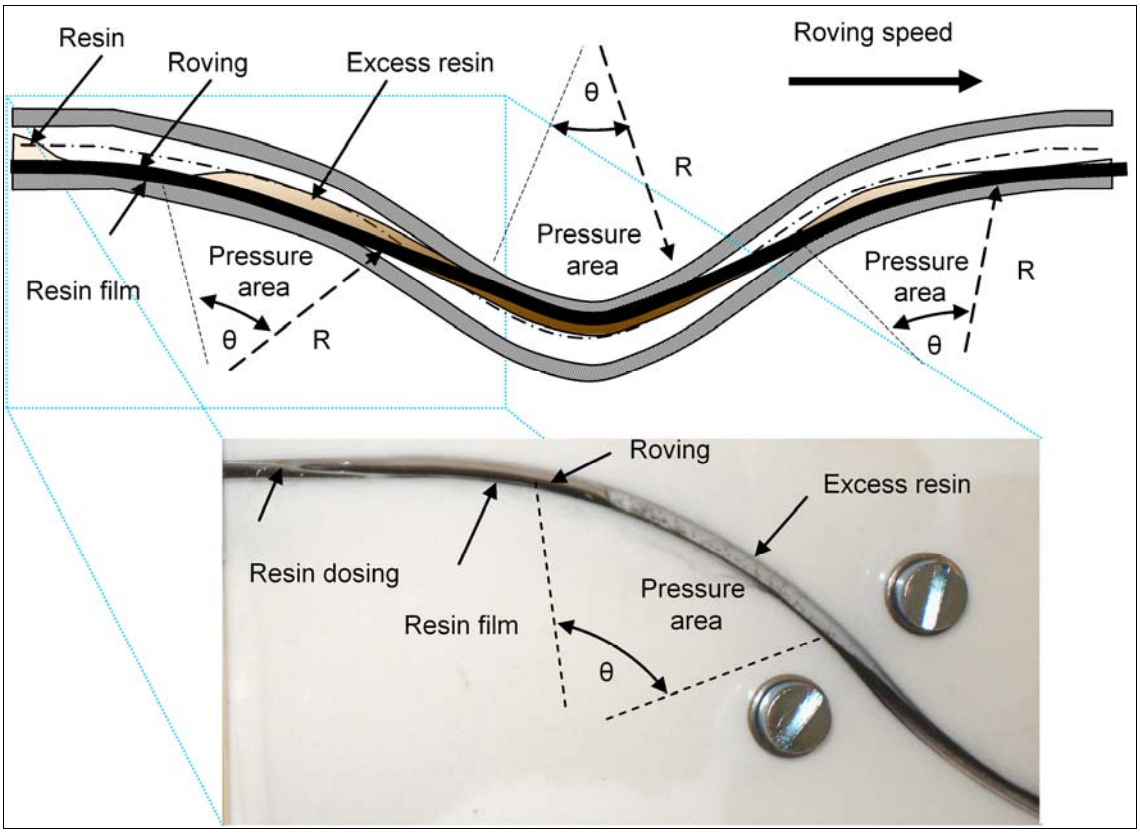

Figure 1: Working principle of the siphon impregnation module.

The total applied tension on the roving is caused by two phenomena. The first one is that during impregnation the thickness of the resin film reduces leading filaments to come into contact with the siphon wall thus causing friction forces to develop. The second one is the pure shear of the resin film. Equation 2 describes the increase of the roving tension during impregnation according to the running arc angle θ where μ is the friction coefficient between roving and surface and f an experimentally defined constant [6].

$$\frac{dT}{d\theta} = \mu T(1-f) + \eta \frac{U}{\delta} RW \qquad [2]$$

Roving tension causes an increase of the resin pressure on the film layer. The pressure on the resin layer is described by Equation 3 where T is the roving tension, W the roving width, and R the curved surface radius.

$$P = \frac{T}{WR} \qquad [3]$$

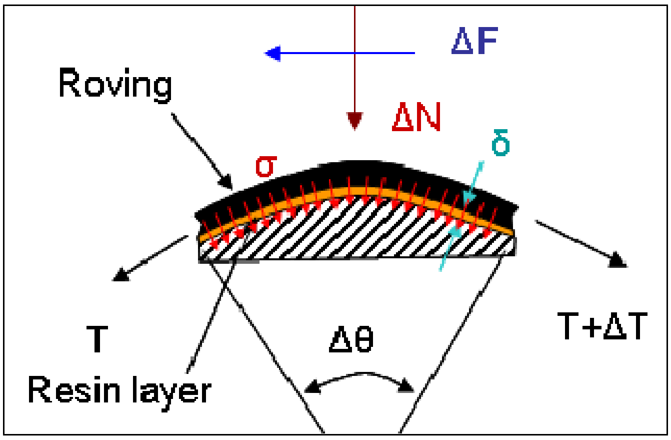

Figure 2: Free body diagram of the roving during impregnation.

The impregnation of the fiber pack takes place due to the pressure rise on the resin film. The pressure acts on the resin layer causing the resin to flow through the permeable roving. The flow can be described by Darcy's law presented in Equation 4 where K is the transverse permeability of the roving and v the flow rate.

$$v = -\frac{K\nabla P}{\eta} \qquad [4]$$

Under the framework of the presented work the efficiency of the siphon was tested for the impregnation of 24k carbon fiber rovings. The results were compared with the results of an open bath impregnation.

MATERIALS

The roving used was the HTS 5631 carbon fiber roving supplied by the company Toho Tenax. The 24k roving consisted of 24.000 single continuous high strength aerospace grade carbon filaments and had a tex. number of 1600. The filaments were treated with a polyurethane based sizing to aid the handling.

The matrix used for the experiments was the epoxy resin system Araldit LY 564 /Aradur 3486 supplied by the company Huntsman Advanced Materials. The system had a viscosity of 200-300 mPa s and a pot life of 560-600 min at room temperature.

EXPERIMENTAL

Goal of the study was to examine the efficiency of the developed impregnation mechanism. Winding experiments over an octagonal mandrel took place. The octagonal mandrel prevents the through the thickness compaction of the roving ensuring that no further impregnation after lay-up will take place. Furthermore, in order to guarantee that the measured impregnation state of the roving will not be further affected, no winding eye (placement unit) was used. The produced samples were single rovings wound in a spiral path over the mandrel. During the winding the effective tension of the roving was monitored. After winding the samples were left to cure at room temperature and a post cure process in an oven took place.

Winding trials with winding speeds of 5, 10, and 15 m/min took place. The resin dosing rate was initially calibrated and set up in order to produce samples with 60, 55, 50, 45, 40, and 35 % of resin weight fraction.

The same experimental set-up was used in order to produce reference samples impregnated though an open resin bath.

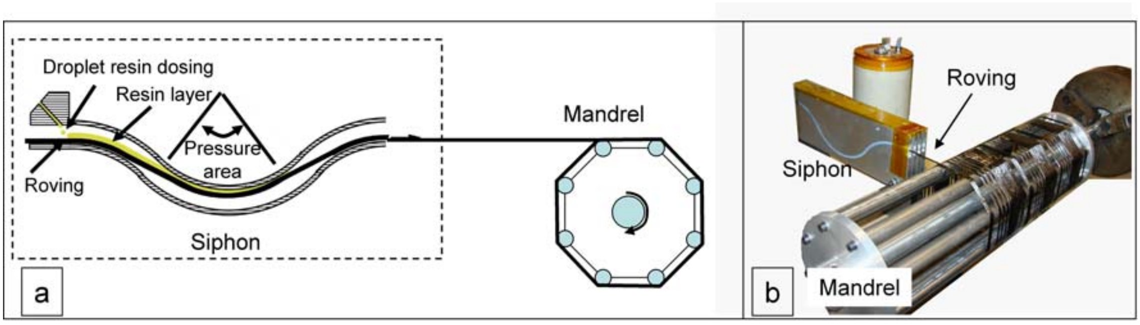

Figure 3: Siphon winding experimental set-up.

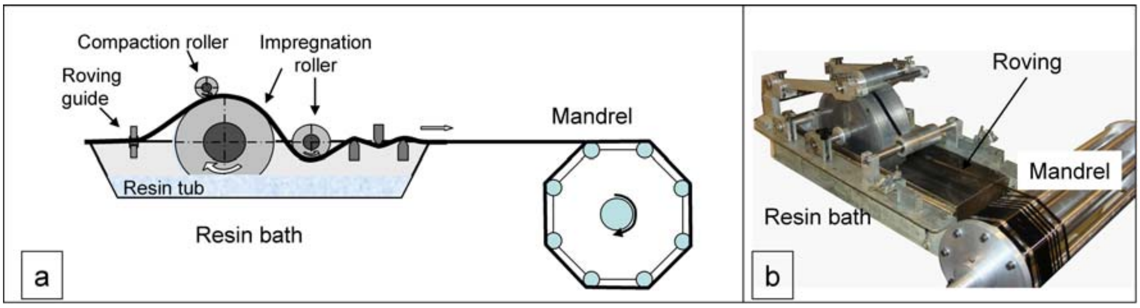

Figure 4: Resin bath winding experimental set-up.

Finally the samples were cut into the appropriate dimensions by use of microtome and were examined under the light microscope. By the use of phase-analysis software the fiber, resin, and voids' fraction were calculated.

RESULTS AND DISCUSSION

The winding trials showed that the siphon can be easily implemented in a filament winding process. By comparing the results between resin bath and siphon it can be seen that the siphon delivers a roving that has a strong elliptic shape. This can be attributed to the fact that the siphon consists of a round tube with an inner diameter of 4 mm. On the other hand the roving impregnated through the resin bath has a high width to thickness ratio. This can be explained by the fact that the roving is strongly spread and compacted as it runs over the impregnation wheel of the resin bath.

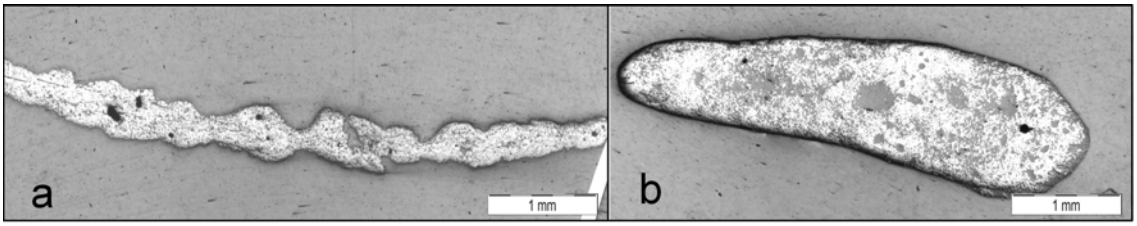

Figure 5: (a) cross section of roving impregnated through resin bath (winding speed 10 m/min), (b) cross section of roving impregnated though siphon (winding speed 10 m/min).

By looking into detail the roving impregnated through the siphon, it can be seen that the filaments are all fully impregnated with resin. The void fraction inside the roving is less than 3 % for all tested set-ups. Based on that, we can come to the conclusion that the pressure on the resin film inside the siphon forces the resin to flow through the entire thickness of the roving leading to a complete impregnation.

Nevertheless the roving impregnated through the open bath has a low void fraction (<3 %), comparable to the roving processed inside the siphon, and a very high compaction rate which leads to a fiber volume fraction of 55 %.

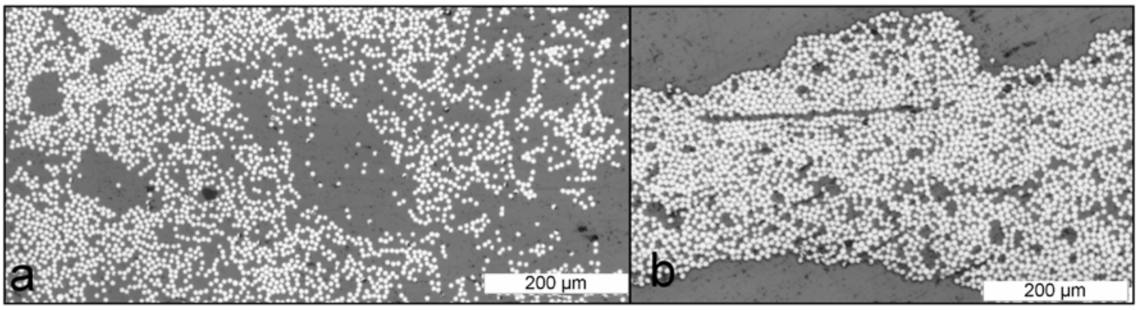

Figure 6: (a) detail of roving impregnated through the siphon (winding speed 10 m/min, 60 % resin weight fraction) (b) detail of roving impregnated through the open bath (winding speed 10 m/min).

The tests with different resin dosing rates proved the ability of siphon to allow the calibration of the fiber/matrix fraction. The final resin weight fraction of the wound samples was found to be analog to the resin dosing rate. The values presented in Table 1 were extracted by microscopically phase analysis.

Table 1: Resin weight fraction of rovings impregnated though the siphon.

Resin weight fraction %	
Set-up	Measured value
60.0	68.1
55.0	56.2
50.0	57.0
45.0	48.0

The resin dosing rate was found to control the compaction of the wound roving. The resin flow rate controls the thickness of the film layer between roving and siphon. By reducing the resin metering rate, the thickness of the resin film between siphon and roving reduces causing more filaments to come into contact with the siphon wall. The increase of the friction leads to increase the applied tension on the roving and thus the compaction forces. Figure 7 shows a detail of a roving impregnated with a high resin dosing rate resulting to a low fiber compaction (case a) and a roving impregnated with a low resin dosing rate resulting to a high fiber compaction (case b).

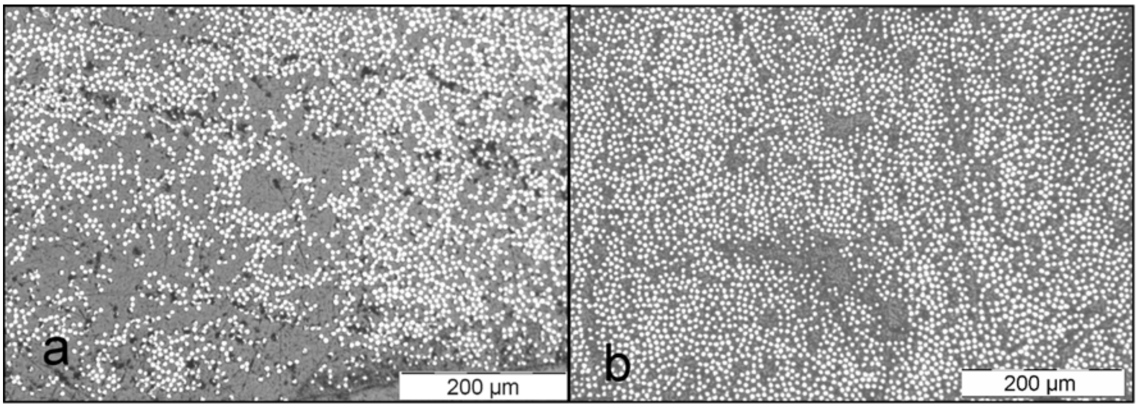

Figure 7: (a) detail of roving impregnated with 55 % resin weight fraction, (b) detail of roving impregnated with 45 % resin weight fraction.

The measurements of the roving tension proved further the dependence between tension and matrix dosing rate. The roving tension values in comparison to the resin dosing rate presented in Figure 8 show that by reduction of the resin dosing rate the tension of the roving increases.

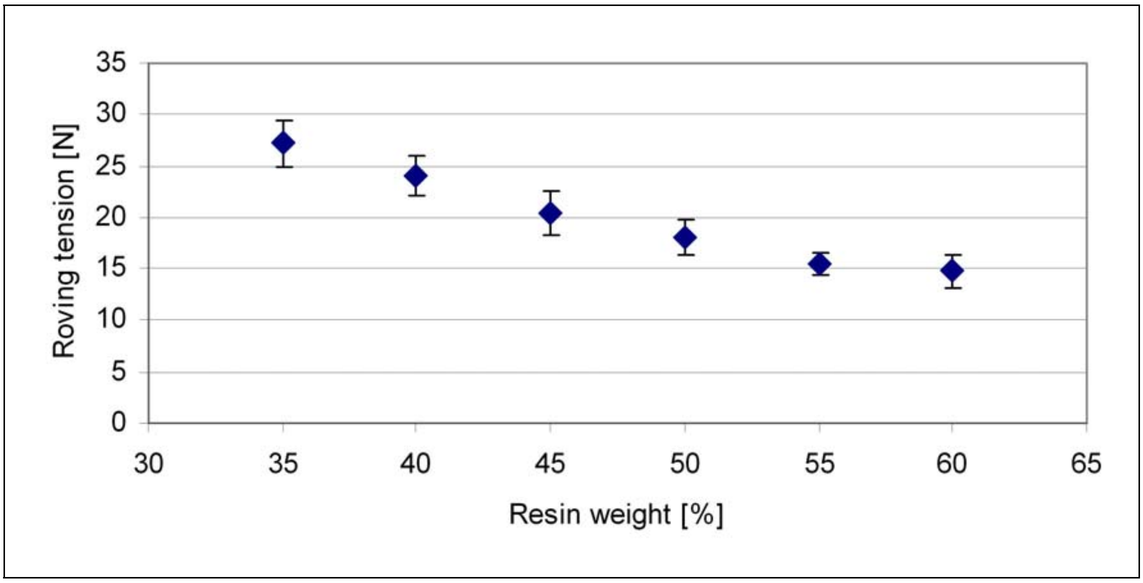

Figure 8: Measured roving tension with different resin dosing rates (winding speed 10 m/min).

Never the less as it can be seen in Figure 9 the roving tension during a long run winding trial remains relatively stable indicating a steady state situation. That means that the friction forces do not cause any local overheating of the resin which could lead to resin gellation.

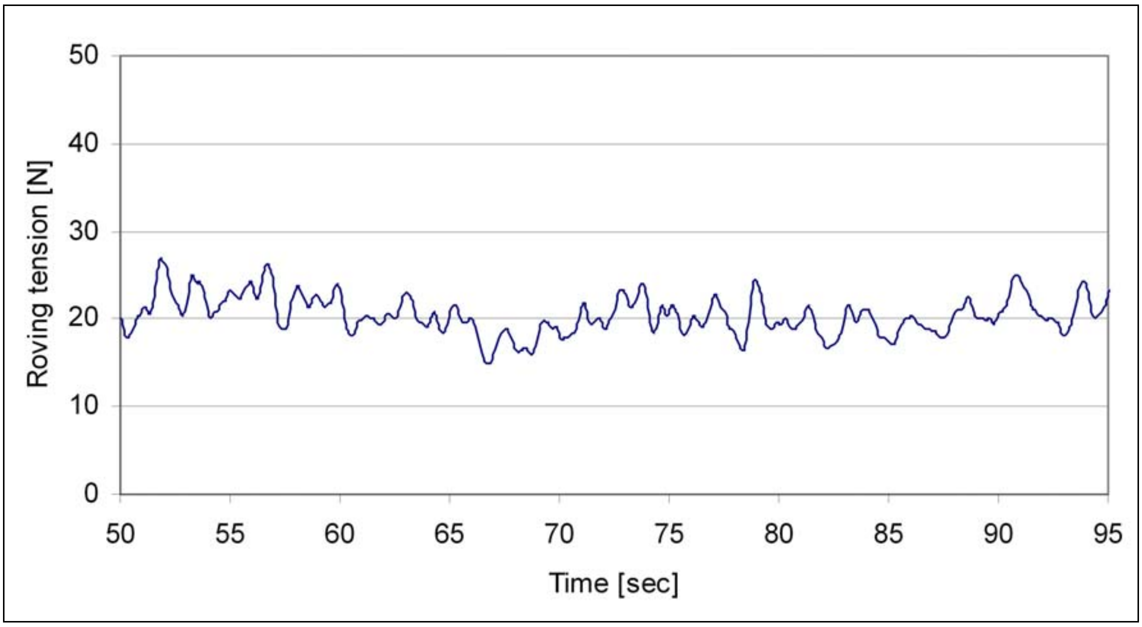

Figure 9: Roving tension over time (45 % resin weight fraction, winding speed 10 m/min).

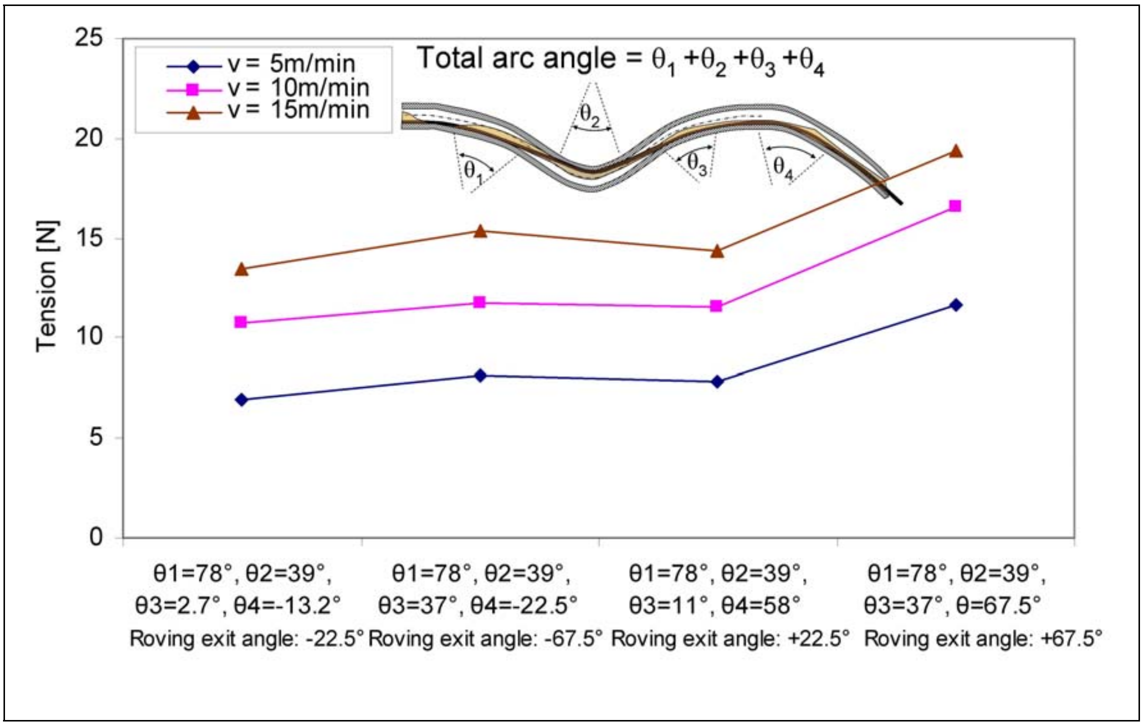

Figure 10: Roving tension over arc angle.

The effect of the siphon geometry was tested by changing the siphon exit angle. By changing the exit angle, the angles θ_3 and θ_4 are affected and thus the total arc length of the roving is in touch with the siphon wall. Increase of the total arc angle causes increase of the normal forces acting on the roving and thus friction and applied tension. Figure 10 shows the dependence between total arc angle and roving tension. Moreover the dependence between process speed and roving tension can be pointed out. The process speed affects the roving tension in 2 ways. By increase of the process speed the shear of the resin film increases and thus the applied tension. Furthermore, increase of the roving pulling speed causes increase of the roving tension on the spool stand before its entry in the impregnation module and thus increase of the final roving tension.

CONCLUSIONS

Under the framework of the presented work a new impregnation method for the filament winding process has been developed. The efficiency of the siphon impregnation has been proved for 24k carbon rovings and for winding speeds up to 15 m/min. The siphon due to its simplicity has the potential of decreasing the labor times and reducing the maintenance costs. Winding tests on an octagonal mandrel allowed the measurement of the impregnation quality of the roving without the effect of the compaction towards the mandrel. The void fraction of the wound roving was found to be under 3 %. The ability of the process to control the fiber/matrix rate was proved. The results showed that contrary to the 2 other online impregnation methods (open resin bath and injection box) a direct control of the fiber volume fraction can be possible. Finally the effective tension force on the roving was monitored. The measured tension values are suitable for the filament winding process and their dependence on the matrix dosing and siphon geometry was investigated.

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