Determination of the friction coefficient in dry-fiber filament winding

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Abstract
Searching for an efficient and repeatable method to produce preforms for Liquid-Composite-Molding (LCM) processes, filament winding of dry rovings can be an option. A critical parameter in the processing of dry fibers is the friction between the roving and the current surface of the mandrel. This importance raises the farther the desired winding path deviates from the geodesic path. The coefficient of friction (also called friction/slippage coefficient) describes the ratio between the normal forces acting on the fibers and the friction force preventing them from slipping. The aim of this study is to validate existing studies concerning the friction coefficient and to examine manipulation methods to increase the friction with respect to dry-fiber winding. Winding speed will be changed as well as the treatment of the mandrel surface. The use of adhesive sprays is identified to be the most effective way to handle dry fibers in a filament winding process in a short term. For more complex processes a suitable binder material is recommended.

1. Introduction

Filament winding is a well-established process for the automated manufacturing of mostly axisymmetric parts. With the use of not-impregnated fibers, it can also be an option to produce preforms fast and accurate [1]. While for simple mandrel geometries geodesic paths can be used, i.e. the shortest distance between two arbitrary points on a surface, for more complex shapes non-geodesic paths must be selected. Here, the winding pattern is determined by the available frictions of the respective surface areas that prevent the rovings from slipping. For concave shapes, fiber bridging has also to be considered [2].
The parameter μ describing the friction between the roving and the surface is called friction coefficient or coefficient of friction (also called slippage coefficient [3]). The slippage tendency λ is defined as the ratio between the geodesic k_g and the normal curvature k_n or the lateral $\overrightarrow{f_l}$ and normal $\overrightarrow{f_n}$ force acting on the surface due to the roving tension [4–12]:

$$\lambda = \left\| \frac{\overrightarrow{f_l}}{\overrightarrow{f_n}} \right\| = \left\| \frac{k_g}{k_n} \right\| \leq \mu \tag{1}$$

The friction coefficient is particularly important as an input parameter for the calculation and simulation of filament winding programs [13].
The determination of the friction coefficient has been the topic of several publications [3, 6, 7, 12, 14]. Common practice is to film the starting point of the slipping during a hoop winding process (winding angle ~90°). This system advanced with the introduction of a specifically shaped mandrel by Koussios and Bergsma [6]. The mandrel surface is described by a function that provides a linear relationship between the feeding eye carriage and the resulting friction coefficient. After a short cylindrical section, the friction coefficient is assumed to rise from zero to one over a distance of 300 mm. Figure 1 shows a drawing of the aluminum mandrel used in this study (based on [3, 6]).

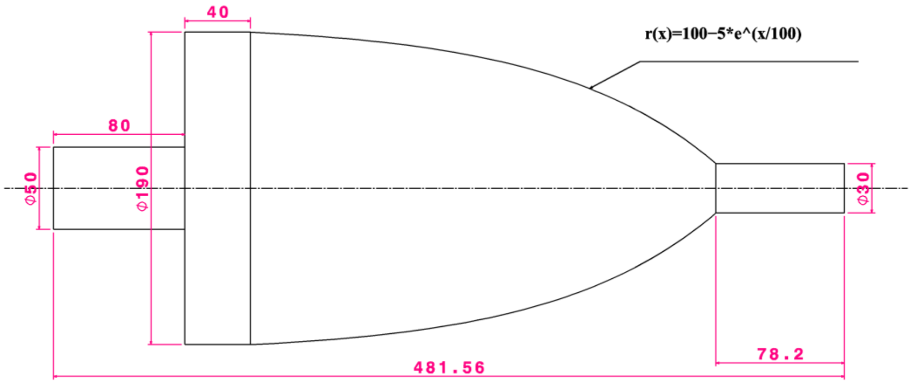

Figure 1. Drawing of the mandrel geometry used in this study.

The previous studies focused on the various process parameters like winding speed and fiber tension and also on the difference between different fiber types, impregnation/curing levels, and roving morphology. Since this work is concentrating on the processing of dry fibers, methods to influence the friction on the mandrel surface are investigated. Hereby, the focus lies on the application of spray adhesives and the use of bindered rovings.

2. Experimental setup

The experiments are performed with a robotic winding setup based on a KUKA Quantec KR 150 R2700 robot. The mandrel is mounted on a KUKA positioning axis KPF1-H250 on a lathe chuck. The process is filmed with a Panasonic® Lumix DMC-FZ300 camera. The fiber deposition is controlled by a self-built end effector. 3D-printed rolls provide fiber guidance and minimize twisting and damaging of the rovings. The mandrel is cleaned after every experiment with isopropanol and additionally with a mold cleaner after the experiments with adhesive spray. Roving tension is measured for every experiment with a handheld tensiometer device Sauter FK250.
Tenax® IMS 65 24K- carbon fiber rovings are used as dry fibers. Tenax® HTS 40 12K carbon fibers are used as rovings with an epoxy powder binder material. Both rovings have a width of approximately 6 mm. The carriage of the deposition system is calculated according to the roving width and the maximum speed of the winding axis. The feeding eye always stays horizontal to the mandrel surface.
Figure 2 shows the setup after a performed experiment.

Figure 2. Experimental setup.

3. Reference experiments

Before mandrel manipulation methods can be evaluated, reference experiments have to be performed. Figure 3 shows the values for the friction coefficient of dry fibers. Additionally, the influence of a winding speed reduction and the pre-treatment of the surface with a mold release agent are investigated.

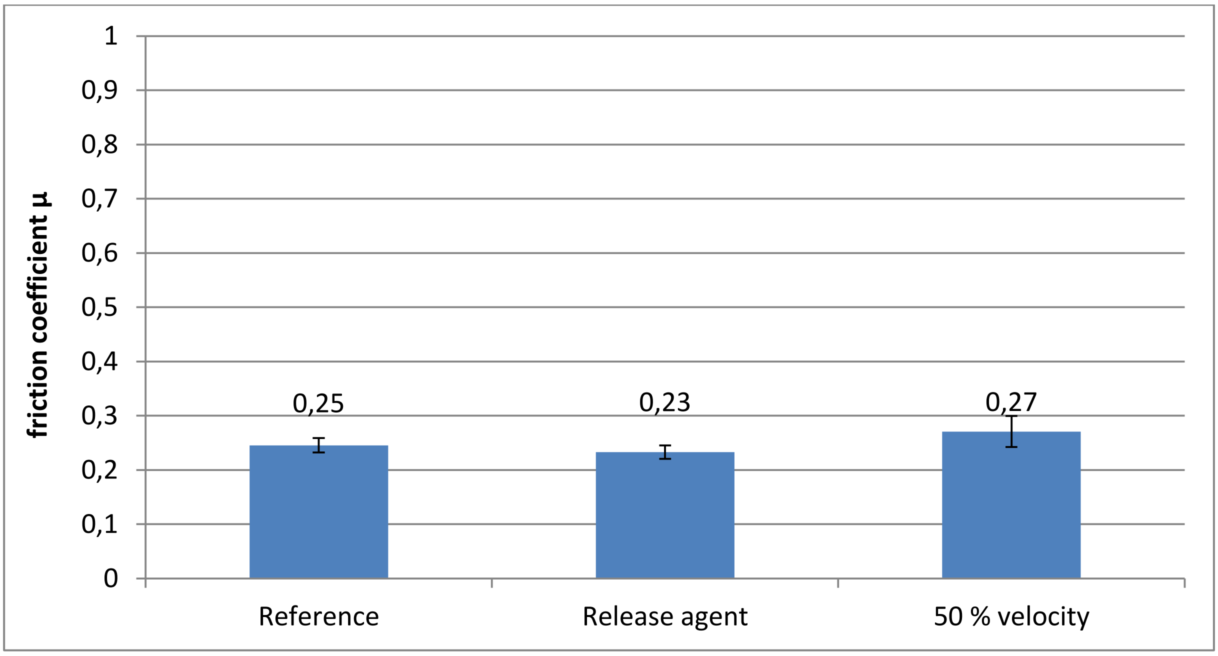

Figure 3. Coefficient of friction for dry rovings.

As pointed out by various studies before [3, 6, 7, 12, 14], the influence of the winding speed can be seen as negligible. Also, the influence of a release agent on the friction behavior of the rovings is not significant. The achieved results correspond well with the existing literature.

4. Influence of different sprays on the mandrel surface

In this section, the manipulation of the mandrel surface by (locally) applying different adhesive and impregnation sprays is investigated. Three different adhesive sprays are tested: Airtac 2E by Airtech Europe S.à.r.l., 3M™ Scotch-Weld77™, and Tesa® Spray Glue by Beiersdorf AG. With reference to [7], PTFE spray is also tested. To examine the influence of oil contamination of the surface WD-40® by the WD-40 Company is applied. Figure 4 shows the results of these experiments.

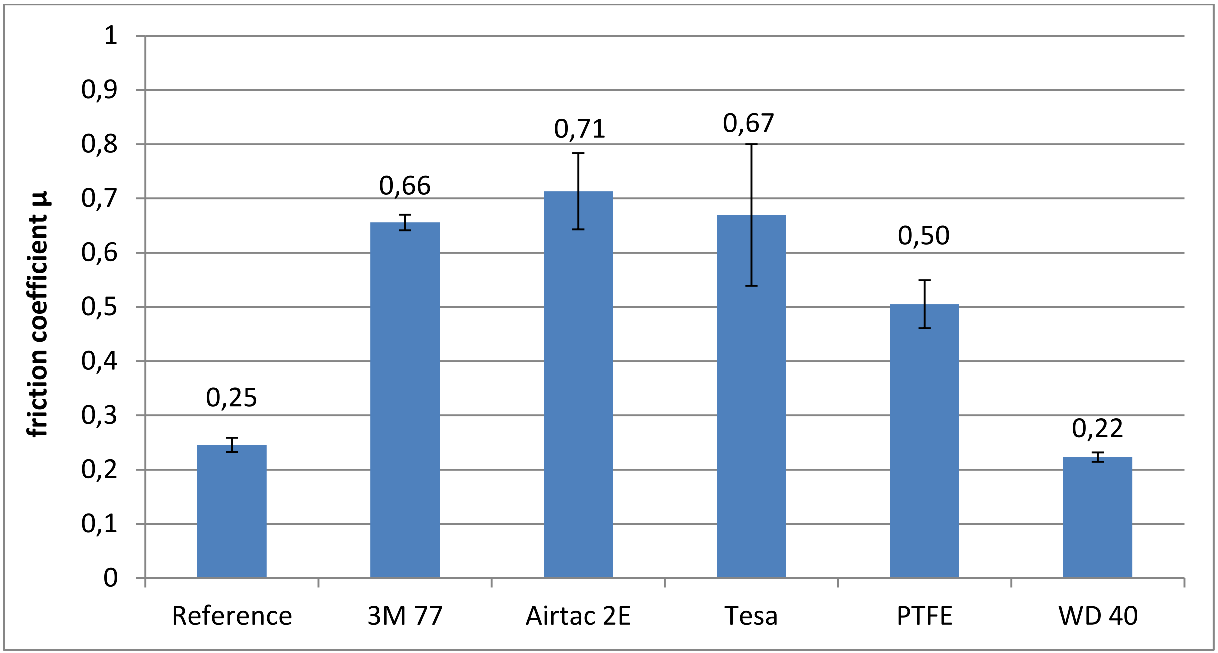

Figure 4. Coefficient of friction after surface treatment with various sprays.

All three adhesive sprays show a significant increase in the friction coefficient. It is sufficient when they are applied in the area where the slippage is assumed to occur. Nevertheless, it is important to apply them circumferentially. If larger areas are not covered with adhesive, slippage will occur and impair the winding pattern. The experiments with an adhesive spray show relatively large standard deviations. This is due to the fact that the point where the slipping starts is hard to determine. Figure 5 shows that the rovings start to overlap in this area. Hence, the rovings may pull apart the already wound layer. They can form a second layer and have consequently no contact with the adhesive. This results in slippage until the contact to the glue is restored or the so-called catastrophic friction, i.e. losing complete adherence to the surface, occurs.
The PTFE Spray has also a positive effect on the friction coefficient. It is even larger than in [7] where it was given by 0,39. In this process, the PTFE forms a thin film on the mandrel with an increased surface roughness compared to the polished aluminum.
The use of WD-40 slightly decreases the coefficient. The interaction between the wetting of the fibers and of the mandrel surface results in only a small deviation from the reference. It can be observed that the fibers get torn apart when slipping due to the wetting of the roving.

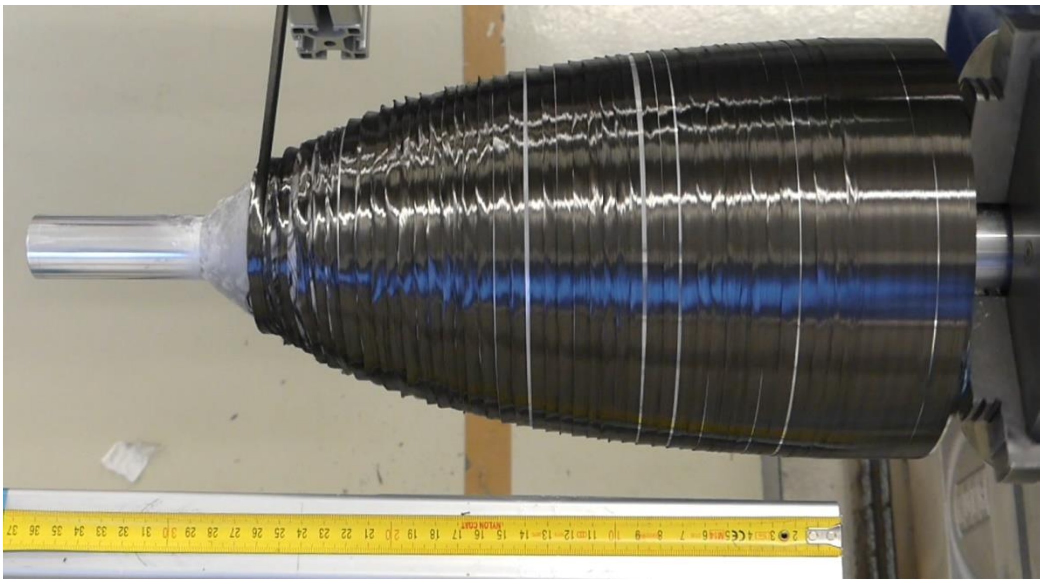

Figure 5. Fiber splitting during an experiment with adhesive spray.

5. Behavior of bindered rovings

As an alternative to dry rovings, rovings impregnated with a binder material can be considered. Binders are commonly based on epoxy resin or thermoplastics. Usually, they need to be activated at a certain temperature. In this study, the roving was first examined without activation. Due to the stiffness of these rovings, they are almost impossible to wind on a conical surface.
Within the framework of these experiments, the on-line activation of the binder by a hot air stream was investigated. The heating times were too short so that the results were very similar to the non-activated rovings. To bypass this problem the mandrel was heated in an oven up to 250 °C. The results of the resulting experiments are shown in Figure 6.

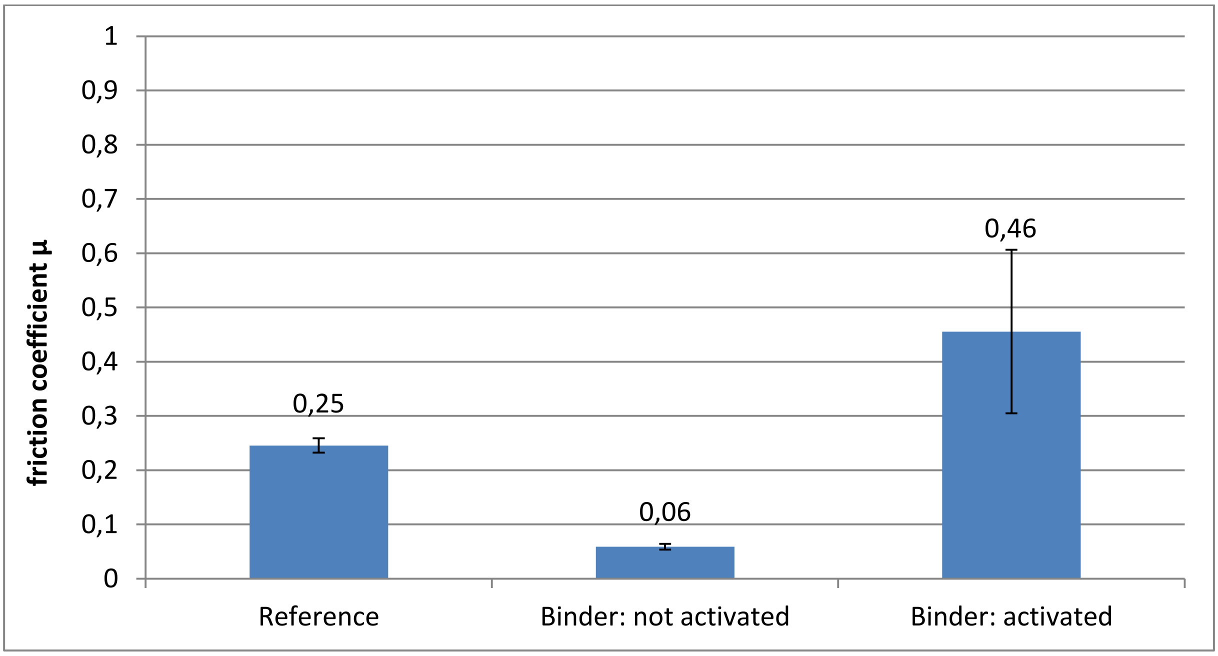

Figure 6. Influence of bindered rovings.

The activated binder shows an improvement in the friction coefficient. Nevertheless, it can still be optimized. A slight slippage of a fiber during the time the roving needs to heat up and activate the binder leads to a displacement of this roving. Consequently, on the next rotation, the roving is laid on the previous one. This effect summons up and leads to a non-uniform winding pattern and finally to the complete slippage. Figure 7 shows the gaps that are created while the binder is activated. It also shows that the current layer is wound on an already existing one.

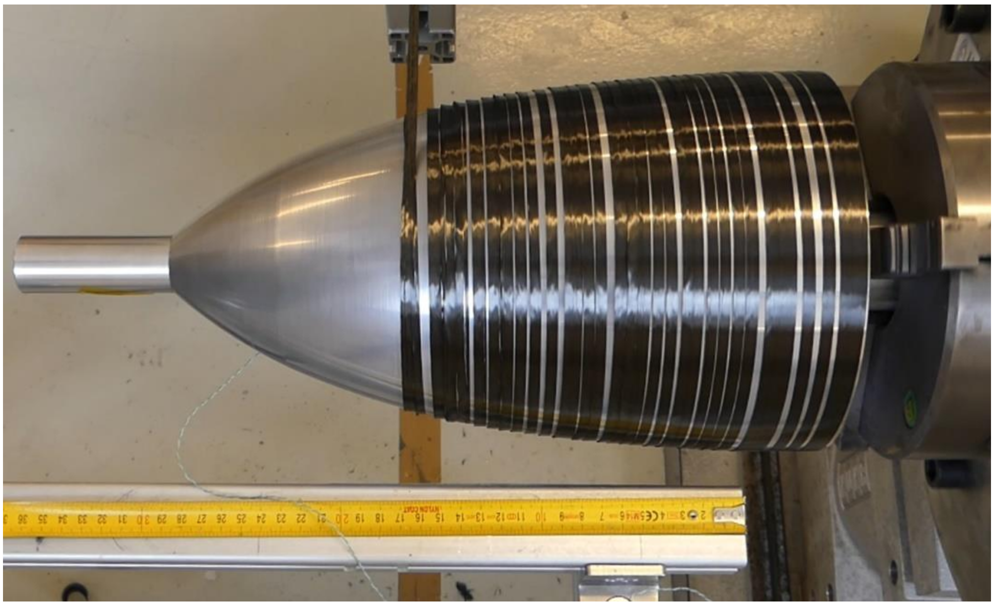

Figure 7. Winding pattern of a bindered roving.

The large value for the standard deviation in Figure 6 can be explained by the degree of activation of the binder at different temperatures. It can be observed that the cooling of the mandrel surface from ~200 °C to ~120 °C leads to better results concerning the coefficient as well as the gaps in the winding pattern. This leads to the conclusion that higher temperatures than an optimized one are counterproductive for the activation of the binder resin system.

6. Conclusion

This paper presents possible solutions to manipulate the friction during the first layer of dry-fiber filament winding processes. The usage of adhesive sprays at the afflicted areas shows significant improvement of the adhesion between fibers and mandrel. Yet, it has still to be investigated which influence the adhesive will have on following resin infusion/impregnation processes. Also, the spraying is not deemed to be a sophisticated method for highly automated and clean processes. Here, the bindered materials would be the preferable solution. Compared to the sprays their adhesive potential has yet to be improved. A key factor will be the installation of an on-line heating system and the determination of the optimal activation temperature of the binder. Additionally, the winding of consecutive layers has to be investigated.

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