# INVESTIGATION ON CREATION OF FIBROUS RINGS AND THEIR INFLUENCE ON THE BRAIDED PREFORM QUALITY

Andreas Mierzwa[1], Christoph Ebel[1], Tobias Harbers[1] and Prof. Dr.-Ing. Klaus Drechsler[1]

[1]Institute for Carbon Composites, Faculty of Mechanical Engineering, Technische Universität München, Boltzmannstraße 15, D-85748 Garching b. München, Germany
Email: mierzwa@lcc.mw.tum.de, Web Page: http://www.lcc.mw.tum.de
Email: ebel@lcc.mw.tum.de
Email: harbers@lcc.mw.tum.de
Email: drechsler@lcc.mw.tum.de

**Keywords:** Braiding, rewinding, fibrous rings, yarn gaps

**Abstract**

During braiding of carbon fiber yarns specific defects may occur, which influence the braiding process stability and the preform quality. One common defect is the fibrous ring, which is a ring-shaped accumulation of carbon filaments on the braiding spool that prohibits the yarn from unwinding. This defect therefore leads to enlarged yarn tension of a single yarn and thus to the creation of a yarn gap, which is a local irregularity in braided preforms. Within this study the origin of fibrous rings and its influence on yarn gap formation is investigated.
Before braiding, the carbon fiber yarn has to be rewound from supplier coils onto braiding spools. The effect of rewinding parameters as well as yarn predamage on the creation of fibrous rings were investigated in a test bench. Therefore an artificial yarn predamage was recreated before rewinding the yarn. It was found that an increased yarn predamage has the most significant effect on the creation of fibrous rings and thus on increasing yarn tension.
Based on the yarn tension investigations conducted at the test bench, a single spool in the braiding machine was impinged with controlled higher yarn tensions. This method created yarn gaps on purpose during the process. It was detected that increased yarn tension of a single yarn led to larger yarn gaps up to a width of 4 mm.

## 1. Introduction

The braiding process chain consists of the braiding itself and an upstream process called rewinding. This process step describes the rewinding of a yarn from supplier coils onto spools that are compatible with the braiding machine. Subsequently the spools are positioned in the bobbins of the braiding machine, where the braid is eventually formed. The upper part of Figure 1 shows a flow chart describing the process chain. In order to guarantee sufficient preform quality it is essential to estimate a defect-free process as early as possible e.g. already during rewinding. The earlier a defect is detected in a process chain the lower are the additional costs that it causes (e.g. rework and waste) [1]. In order to estimate the risk of defect creation during braiding, it is necessary to analyze crucial parameters that lead to defects and therefore to deteriorated mechanical properties of the braid or machine downtime [2]. The formation of braiding-specific defects is influenced by two groups of factors. Once the machine parameters like rewinding and braiding parameters (including yarn tension). The second group consists of yarn parameters like sizing (type/amount) and yarn quality respectively the yarn predamage.

Excerpt from ISBN 978-3-00-053387-7

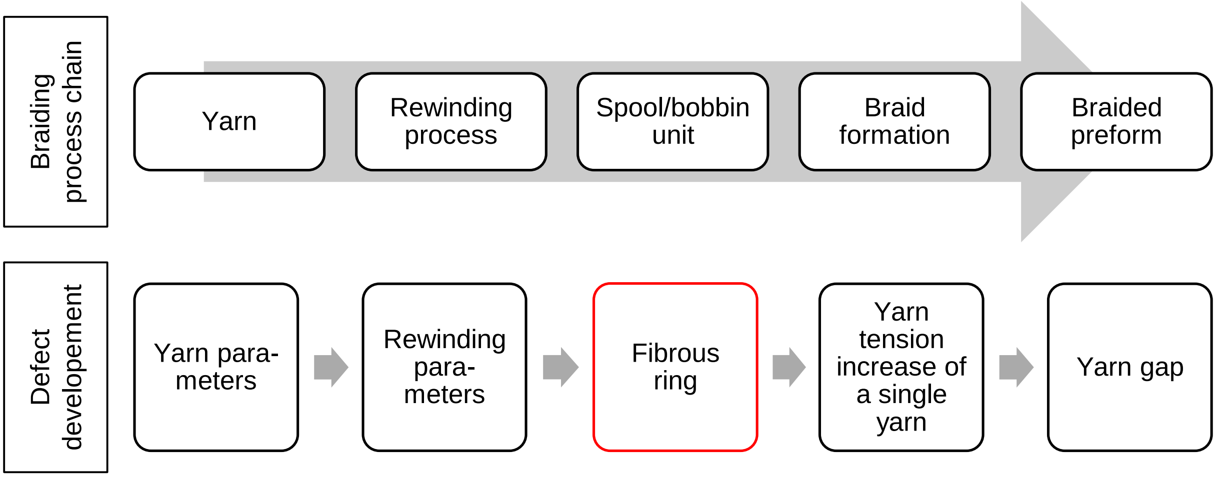
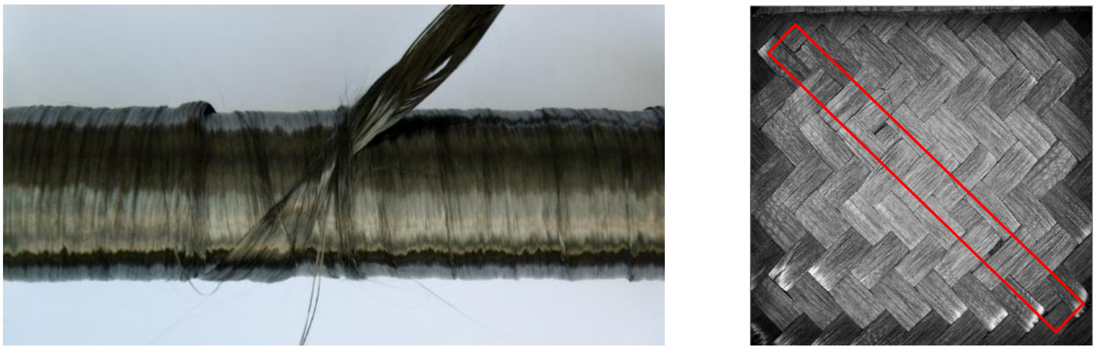



**Figure 1:** Development of yarn gap during the braiding process chain

Based on a failure possibility analysis fibrous rings were detected as most crucial braiding specific defects (highlighted in red in the lower part of Figure 1). The fibrous ring prohibits the yarn from being unwound from the braiding spool (Figure 2a) and creates an increase of yarn tension. Respectively this yarn has a larger yarn tension than the remaining braiding yarns. Therefore irregularities during formation of the braid develop and a yarn gap arises (Figure 2 b). Furthermore the analysis showed that a fibrous ring can be traced back the process chain (Figure 1). The fibrous ring has its origin in rewinding parameters and yarn quality. This study focuses on finding the most curial parameter among the rewinding and yarn parameters which lead to fibrous rings.



a b

**Figure 2.** Fibrous ring (a) and yarn gap in a braided preform (b)

Excerpt from ISBN 978-3-00-053387-7

## 2. Yarn damage

As described in [3] yarn damage may be divided in six damage levels. Level 0 describes a virgin fiber which comes directly from the supplier coil, has a defined width and feels stiff to the touch (depending on the sizing amount). The subsequent levels (1-2) define a damage on microscopic level. Level 1 describes sizing damage, which is visible by an irregular yarn width, matt surface and soft touch. Level 2 is therefore defined by broken filaments protruded off the yarn structure. Figure 3 shows an overview. Damage levels 3 to 6 like filament accumulation or yarn breakage are not relevant for this study.


**Figure 3.** Yarn damage levels [3]

Due to different yarn manufacturing parameter and sizing amounts yarns may reach damage level 2 directly from the supplier coil. Because the yarn was not damaged by a subsequent process step, the term “predamage” is used in this paper.

## 3. Rewinding trials

The following sketch (Figure 4) shows the principal of rewinding, which always consists of a supplier coil on a creel and the braiding spool in the rewinding machine.

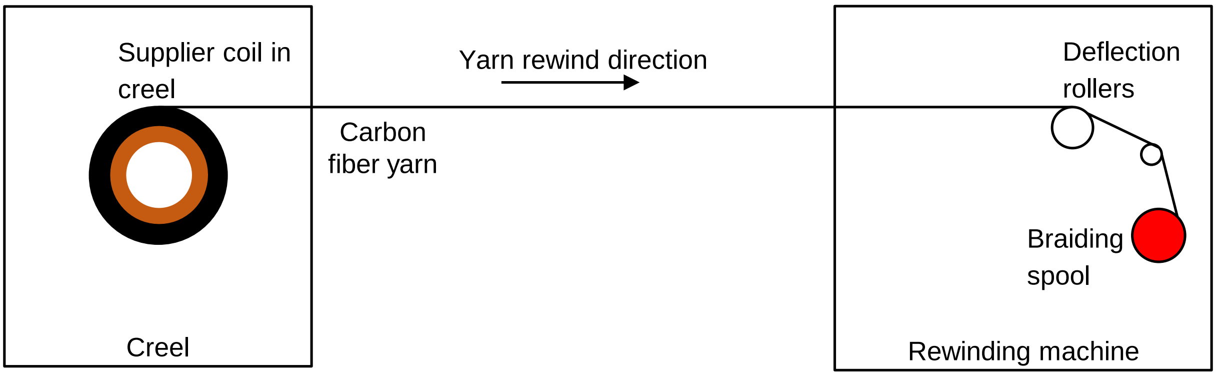



**Figure 4:** Creel and rewinding machine

The bobbin creel generates a defined yarn tension using a hysteresis brake while the rewinding parameters are adjusted manually at the rewinding machine. These include the rewinding speed respectively the rewinding revolutions. Additionally to these standard parameters for the trials a yarn predamage is brought to the yarn by a rod shortly after the creel (Figure 5). The rod is prepared with sand paper in order to predamage the yarn in terms of filament breakage. The rough surface of the sand paper creates sufficient friction in order to exceed the tensile strength of a single filament.

Excerpt from ISBN 978-3-00-053387-7

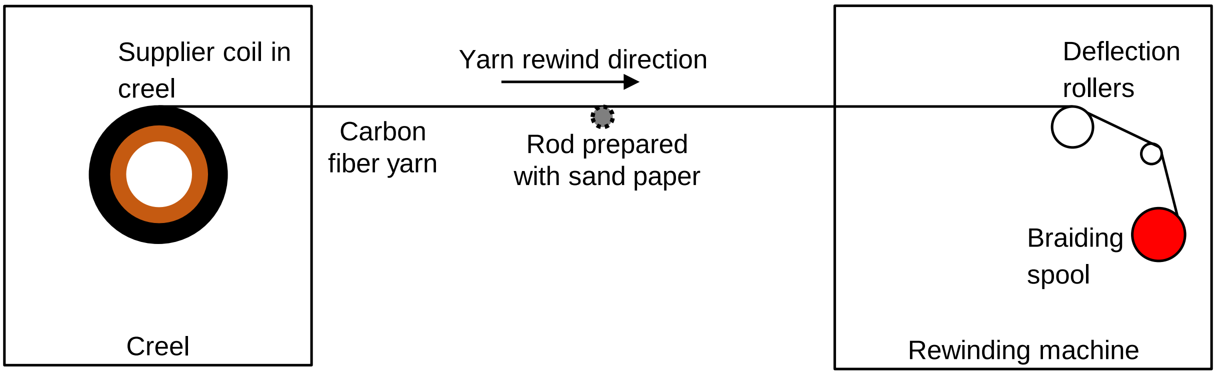



**Figure 5.** Creel and rewinding machine with additional rod prepared with sand paper

A 24 k HT carbon fiber yarn was used with a yield of 1650 g/km, 0,3 wt% of epoxy sizing. Every spool had a yarn length of 50 m. The sand paper was replaced after every rewinding trial. A design of experiments approach was created using the four factors with different factor levels: Yarn tension (4 N, 8 N, 16 N), rewinding revolutions (20 rpm; 200 rpm), yarn quality (virgin yarn or predamaged yarn).

## 4. Unwinding trials

In order to evaluate the rewinding parameters respectively the yarn parameters an unwinding test bench was built. It has the purpose to unwind the yarn from the spool equally to the unwinding process during braiding. Figure 6 shows the principle of the unwinding test bench. It consists of a bobbin, a camera, a yarn tension instrument, which is at the same time the first deflection and an electric motor. A single spool, which was rewound in the rewinding trials, is inserted in the bobbin. The bobbin preserves the yarn at a tension of 3,5 N (±1 N) controlled by an embedded compression spring. The unwind velocity at the test bench is equal to the unwind velocity during the braiding process. In this case v = 39 mm/s. This yarn velocity was calculated for a braiding process with the following parameters:

- cylindrical core with a diameter of 65 mm
- 100 % fiber coverage
- braiding angle of 45°
- 130 rpm of the horn gears
- 64 bobbins

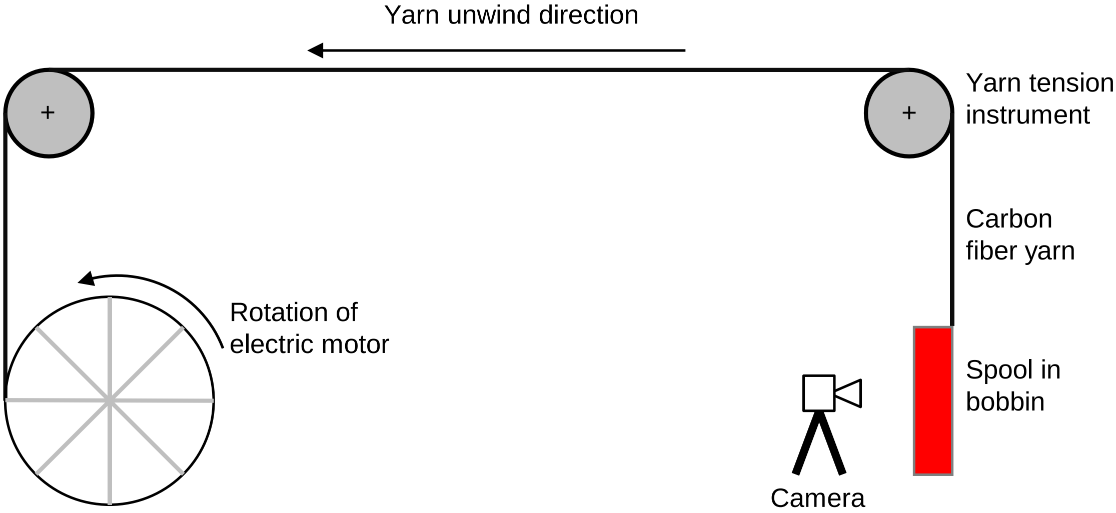



**Figure 6.** Unwinding test bench

Excerpt from ISBN 978-3-00-053387-7

If a fibrous ring is formed the camera records its formation while the yarn tension instrument records the yarn tension change. Figure 7 illustrates an example of the correlation between fibrous ring formation and yarn tension increase over time.
This exemplary spool was rewound of predamaged yarn and generates two separate fibrous rings during unwinding. Continuous and dashed circles connect the diagram and the pictures. The fibrous ring highlighted in continuous circles is described first. A normal unwinding behavior with 3,5 N (±1 N) is notified till the first peak at approx. 5 min (11,7 m). This peak reaches 11 N. By analyzing the video recording closer, it is visible that this ring (continuous circle) stays at same position in every layer which is unwound (picture on bottom right). The yarn is passing by this position and a yarn tension increase is recorded at 5 min, 11 min, 13 min and 15 min. The peak of 21 N at 15 min leads to the interruption of the process in order not to damage the bobbin. At the position of 8 min no change is recorded. The reason why the yarn tension at this point does not increase, requires more investigation.

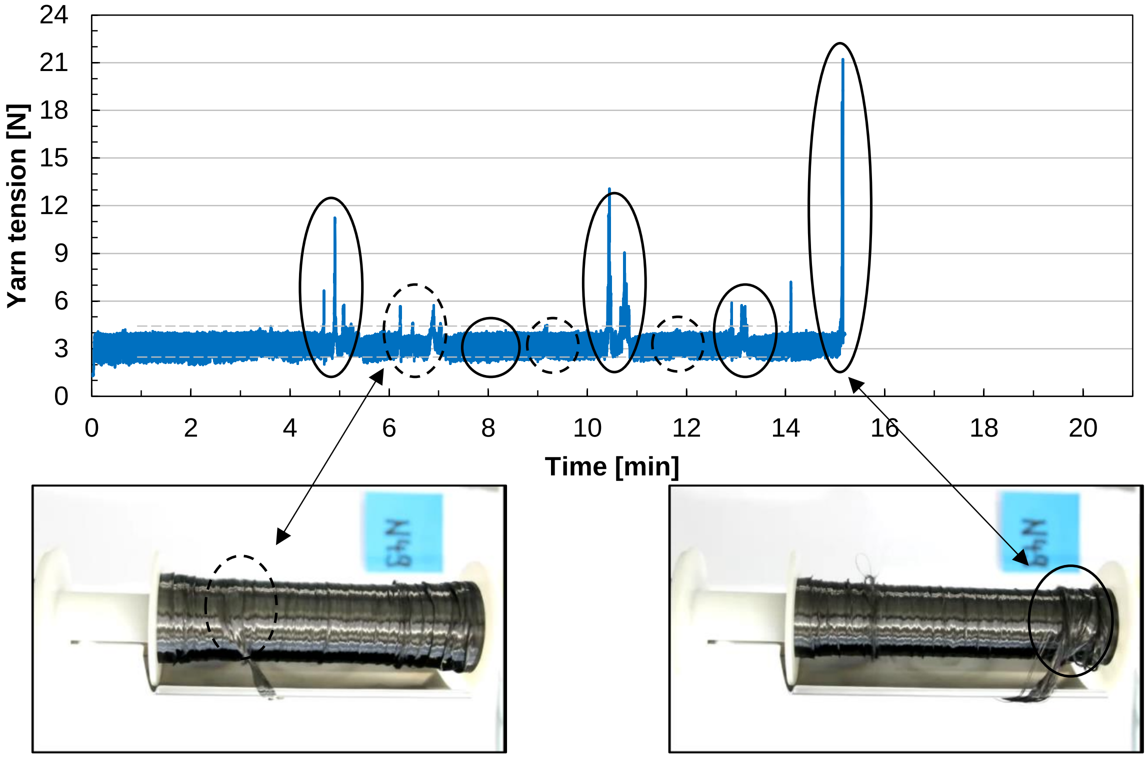



**Figure 7.** Yarn tension correlated to fibrous ring formation

The fibrous ring highlighted with the dashed circles shows similarities and differences to the first fibrous ring. The “dashed” ring stays at the same position (picture on the bottom left; Figure 7) but does not show similar fiber tension increases. The very local influence of the fibrous ring and the fact that not always a yarn tension increase is created, have to be investigated in detail in further investigations.

If the results of the unwinding trials are compared with the rewinding parameters, it shows that yarn predamage is the most crucial parameter that leads to fibrous ring formation. The second most important parameter is the yarn tension during rewinding. The following model (Figure 8) describes a possible explanation for the ring formation and the influence of yarn predamage and yarn tension during rewinding.

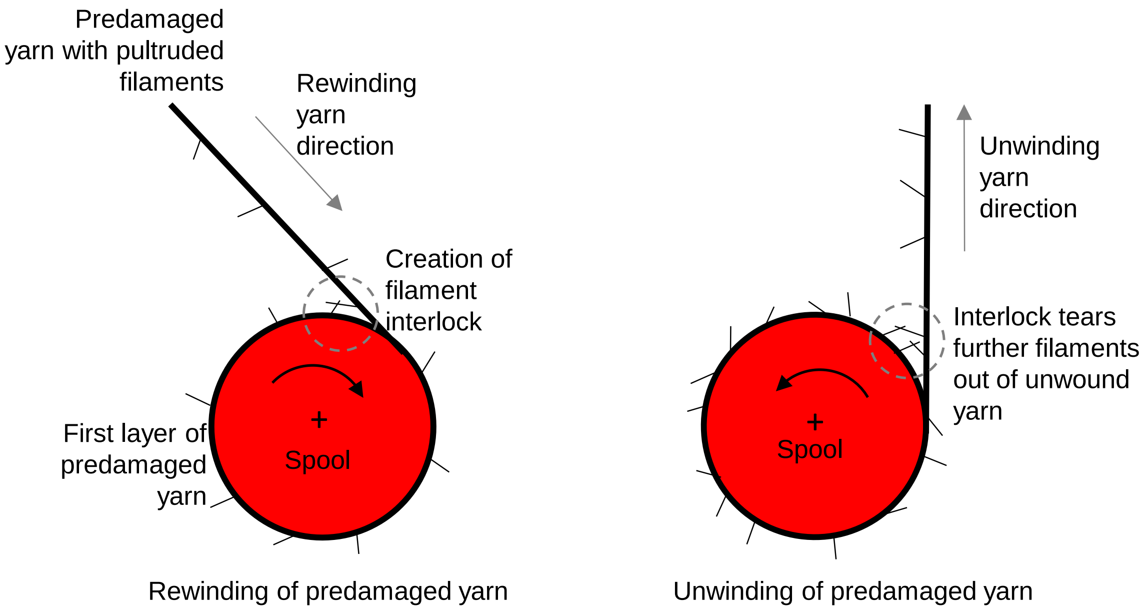



**Figure 8.** Model of fibrous ring formation during unwinding

If a layer of predamged yarn is already placed on the braiding spool and a further layer of predamaged yarn is rewound on top of it, the pultruded filaments of these layers may interlock (Figure 8). During unwinding, this interlock tears additional filaments out of the yarn, which is unwound. These remaining filaments accumulate in terms of a fibrous ring. This behavior dependents on the number of pultruded filaments. Thus an undamaged yarn (damage level 0) tends to create no interlocks, which leads to a defect-free unwinding. Furthermore this effect of interlocking depends also on the compaction of the yarn material on the bobbin. This therefore explains that with higher yarn tension the risk of fibrous ring formation increases as well.
The rewinding revolutions per minute did not show any influence on the fibrous ring formation.

## 5. Braiding trials

Based on the dynamical yarn tension increases recorded at the unwinding test bench (Figure 7) a yarn tension table was deviated. This table covers the dynamic yarn tension increase in finite steps which is shown in Figure 9. Yarn tensions are selected from 3,5 N (normal yarn tension) till 18 N.

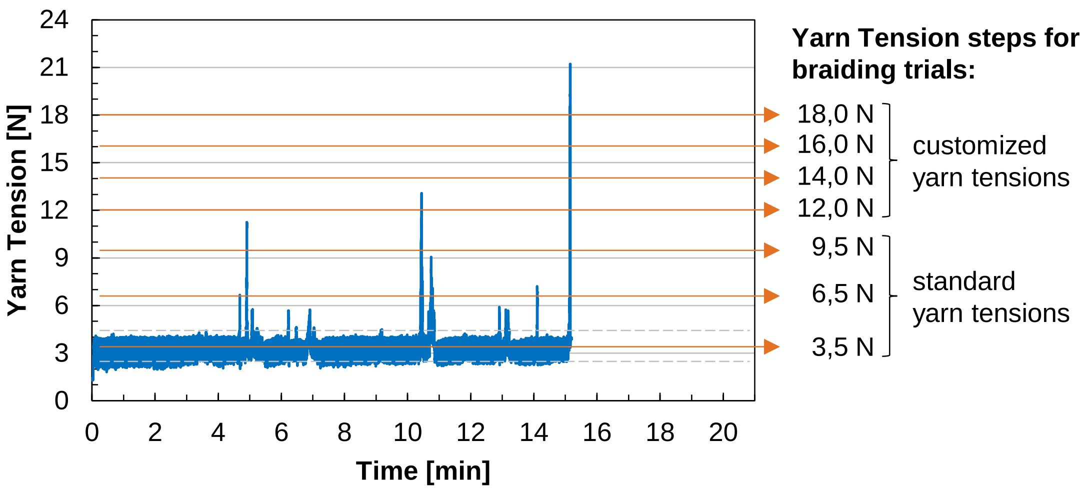
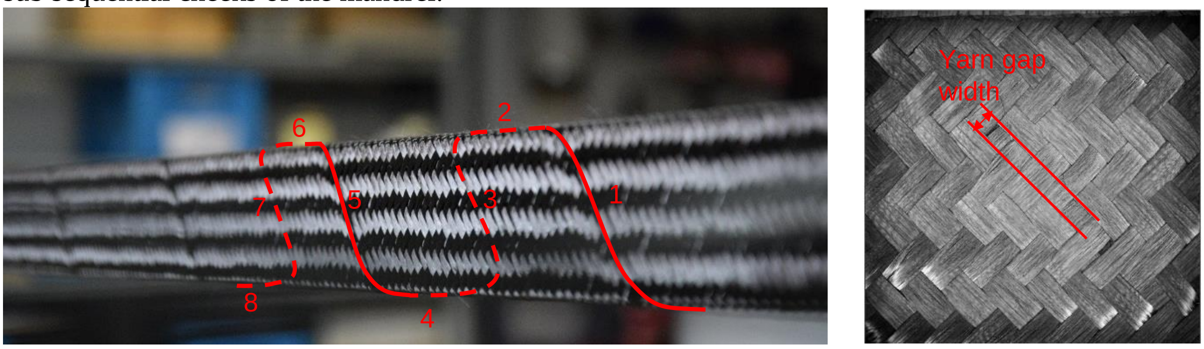



**Figure 9.** Yarn tension table

The braiding trials were performed on a radial braiding machine creating a preform with a braiding angle of 45°. The braiding specific details were already shown in paragraph 4. A single bobbin inside

Excerpt from ISBN 978-3-00-053387-7

the braiding machine was impinged by a harder compression spring in order to increase the yarn tension on purpose regarding the yarn tension table. In order to measure the yarn gaps an optical measurement system (Profactor®) was used. Due to the limited depth of focus of the system a mandrel with a square-shaped cross section was used rather than a cylindrical one. The results are based on 8 measurements taken from one preform. A gap runs in a helix-shaped path which is illustrated in Figure 10 a. The dashed line illustrates the not visible gap path on the mandrel top, bottom and back side. The yarn gap measurement is defined by the distance rectangular between the edges of the yarns, which create the gap (Figure 10 b).
With the optical system one picture per position was taken. The main yarn gap (generated by the enlarged yarn tension) in the middle of the picture was measured. In total 8 pictures were taken of 8 sub sequential cheeks of the mandrel.




a b

**Figure 10.** Gap path on square-shaped mandrel-front side (a) and yarn gap width measurement with optical system (b)

The gap formation was investigated for all yarn tensions shown in the yarn tension table. Figure 11 shows in summary the measured yarn gaps versus the yarn tension of a single bobbin (regarding the yarn tension table). An increase of approx. three times the regular yarn tension (3,5 N) produces a gap width of 2,5 mm. The higher the yarn tension increases, the larger becomes the yarn gap width. Although a plateau is visible at 14 N and 16 N. The largest values were measured at a yarn tension of 18 N creating a yarn width of approx. 4 mm. This correlates with an average yarn width of the used 24 k HT yarn with a braiding angle of 45°.

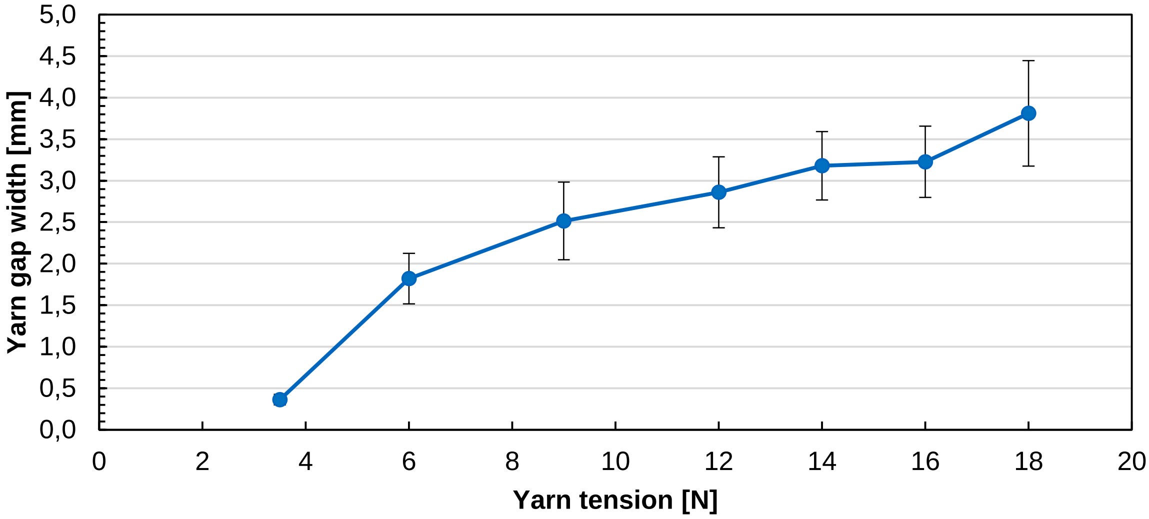



**Figure 11.** Yarn gap width versus yarn tension of a single yarn

During braiding with the standard yarn tension of 3,5 N a standard gap width of 0,5 mm occurred.

Excerpt from ISBN 978-3-00-053387-7

## 6. Conclusion

Based on an analysis of the braiding process, the fibrous ring was determined to be one of the most crucial braiding defects. This defect is a ring-shaped accumulation of carbon filaments on the braiding spools that prohibits the yarn from unwinding. Based on the process analysis, it was found out that especially the yarn predamage has an influence on the fibrous ring formation. The correlation between yarn predamage and fibrous ring formation has been confirmed by rewinding and unwinding trials. The fibrous ring causes a dynamic tension increase which was investigated in a range from 3,5 N (standard yarn tension for a 24 k yarn) till 20 N. Based on the dynamical yarn tension increases a yarn tension table was deviated. In total seven different yarn tensions were impinged on a single bobbin in the braiding machine. The different yarn tension created controlled yarn gaps in braided preforms. These yarn gaps were measured with an optical measurement system and were correlated with the appropriate yarn tension. It was found out that a higher yarn tension causes a larger yarn gap up to 4 mm which equals one yarn gap width (24 k fiber yarn).

## 7. Outlook

Further investigations will be necessary in order to measure yarn predamage quantitatively and evaluate the risk of fibrous ring formation before braiding e.g. during or before rewinding. This offers the chance of creating an incoming good control specified for the braiding process. As described in paragraph 4 the local effect and the behavior of fibrous rings is not completely understood and has to be analyzed in more detail.

Further investigation have to be performed in order to clarify the effect of gaps on mechanical performance. The method of recreating a defect may be applied in this case as well. Composite coupons have to be provided by defined gap widths and gap positions in order to correlate reduced mechanical performance to gap configurations.

The measurements presented in this paper were restricted to a yarn tension of 20 N. But a fibrous ring may lead to yarn tensions higher than 20 N. Therefore bobbin damage or yarn breakage during the braiding process are possible which both lead to machine down time. In this case the incoming good control may be extended to correlate with the productivity of the braiding process.

## References

[1] E. Hering, J. Triemel, H.-P. Blank. *Qualitätsmanagement für Ingenieure*. Springer Verlag, 2003.

[2] C. Ebel, M. Brand, K. Drechsler. Effect of fiber damage on the efficiency of the braiding process. *Proceedings of the 11th composites week @ Leuven and TexComp-11 conference, Leuven, Belgium, September 16-20 2013.*

[3] Y. Kyosev. *Advances in Braiding Technology*. Woodhead publishing series in textiles, 2016.

Excerpt from ISBN 978-3-00-053387-7