Formed Pultrusion Profiles

Wrinkle-Free Forming of Pultruded Hollow Profiles by Local Stretch Bending

Pultrusion profiles are typically inexpensive, stable – and one-dimensional. Local stretch bending represents a new approach to forming thermoplastic pultrusion profiles.

Comparison of fiber wrinkling on a test specimen produced by local stretch bending (above) and a test specimen produced by draw bending (below)

© Fraunhofer ICT

Pultrusion is an inexpensive process for the production of fiber-reinforced composite structures. Cost-sensitive sectors such as the automotive industry therefore have a strong incentive to use pultrusion profiles for the local reinforcement of structural components. In certain cases, it is also conceivable to assemble structural components from pultrusion profiles. However, the typically one-dimensional geometry of pultrusion profiles often requires the use of complex joining elements or compromises in component design. The use of thermoplastic matrix materials, for example via melt pultrusion or reactive thermoplastic pultrusion, allows the subsequent forming of pultrusion profiles. This offers the potential to overcome the above-mentioned obstacles and therefore expand the range of applications for pultrusion profiles. Currently, however, there is a lack of manufacturing processes that allow local and flexible forming of the profiles while maintaining basic quality requirements.

Within the framework of the Unist-HIM project, Fraunhofer ICT, together with the Fraunhofer Project Center for Composite Research at the Ulsan National Institute for Science and Technology (FPC@Unist) and the other Korean partners Large Co. Ltd., LG Hausys Ltd., Katech, SKC and Dyetec, is developing manufacturing processes for the forming of thermoplastic-impregnated semi-finished composite products, which are available either as hollow intermediate materials (HIMs) or sandwich intermediate materials (SIMs). The focus of Fraunhofer ICT is on the forming of pultruded tubes with unidirectional (UD) fiber orientation,

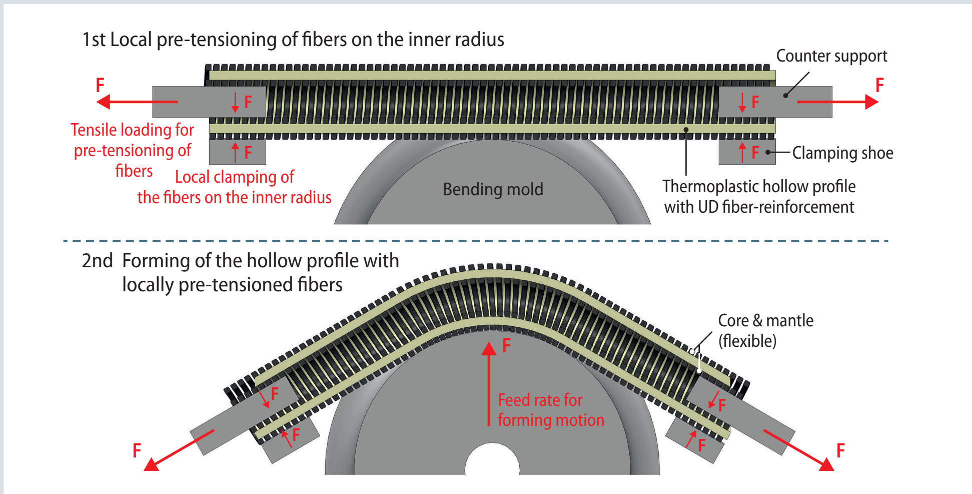

Fig. 1. Conceptual diagram of local stretch bending Source: Fraunhofer ICT; graphic © Hanser

which offer high section moduli and stiffness with low mass and low material input. The objective of "local stretch bending" is to combine this advantage with geometric flexibility by allowing local and flexible forming of the profiles.

The Principle of Local Stretch Bending

The development of the local stretch bending approach is based on an analysis of the mechanical stresses that occur during the forming or bending of profiles: tensile stresses on the outer radius and compressive stresses on the inner radius. The latter typically cause wrinkling, which has a negative effect on the mechanical and optical properties of the profile. In the local stretch bending approach (**Fig. 1**), these compressive stresses are eliminated by selectively pretensioning the continuous fibers located on the inner radius during the forming process. For this purpose, the fibers are locally clamped and tensioned using special clamps before the profile is heated. This tensile load is maintained throughout the entire forming process (heating, forming, cooling) so that the continuous fibers remain taut at the inner radius and wrinkling is avoided. During the forming process, the remaining, non-pretensioned, continuous fibers are guided by a core and a mantle (each of which is a flexible metal bending spring), so that other typical damage mechanisms such as collapse of the profile cross-section or matrix failure are also avoided. Since the length of the continuous fibers remains constant, they must slide against each other during the forming process so that the ends of the profile emerge at an angle after forming.

Fig. 2. Hollow profile formed by local stretch bendin © Fraunhofer ICT

Validation of the Approach and Investigation of Process Parameters

In preliminary tests, the effectiveness of the approach described above was demonstrated by means of bending tests on an automated test rig. Here, pultruded tubes with a length of 330 mm, an outer diameter of 20 mm and a wall thickness of 3 mm, consisting of a PETg matrix with 60 wt.% UD glass fiber-reinforcement, were formed by local stretch bending. With a bending radius of 93 mm, the profiles could be bent almost without wrinkling, up to an internal angle of approx. 130° (**Fig. 2**). The use of the core and the mantle also prevented collapsing of the cross section and matrix failure. The inclined ends resulting from the forming process were subsequently removed. Due to the mechanical clamping of the continuous fibers located on the inner radius, wall thickness variations occur at the profile ends. However, these do not extend through the entire profile, but are no longer visible at a distance of 40 to 50 mm from the end of the profile.

In order to better understand the process of local stretch bending, the influence of some central process parameters on the bending result was analyzed in a DoE (Design of Experiments) study. For this purpose, the test specimens described above (bending radius: 93 mm, internal angle: 130°) were produced with varied process parameters. In addition to the process temperature (temperature of the profile at the beginning of the forming process), the forming movement was investigated. From the preliminary tests it is known that a stepwise forming movement allows a more stable process as well as significantly reduced wrinkling compared to a continuous forming movement. A controlled sliding of the continuous fibers can only be achieved by stepwise forming. Consequently, the step length (feed path per forming step), the forming speed (speed at which the forming steps are carried out) and the holding time (delay between two consecutive forming steps) were also varied.

Fiber wrinkling was considered the most important quality feature of the formed profiles. In order to quantify this non- »

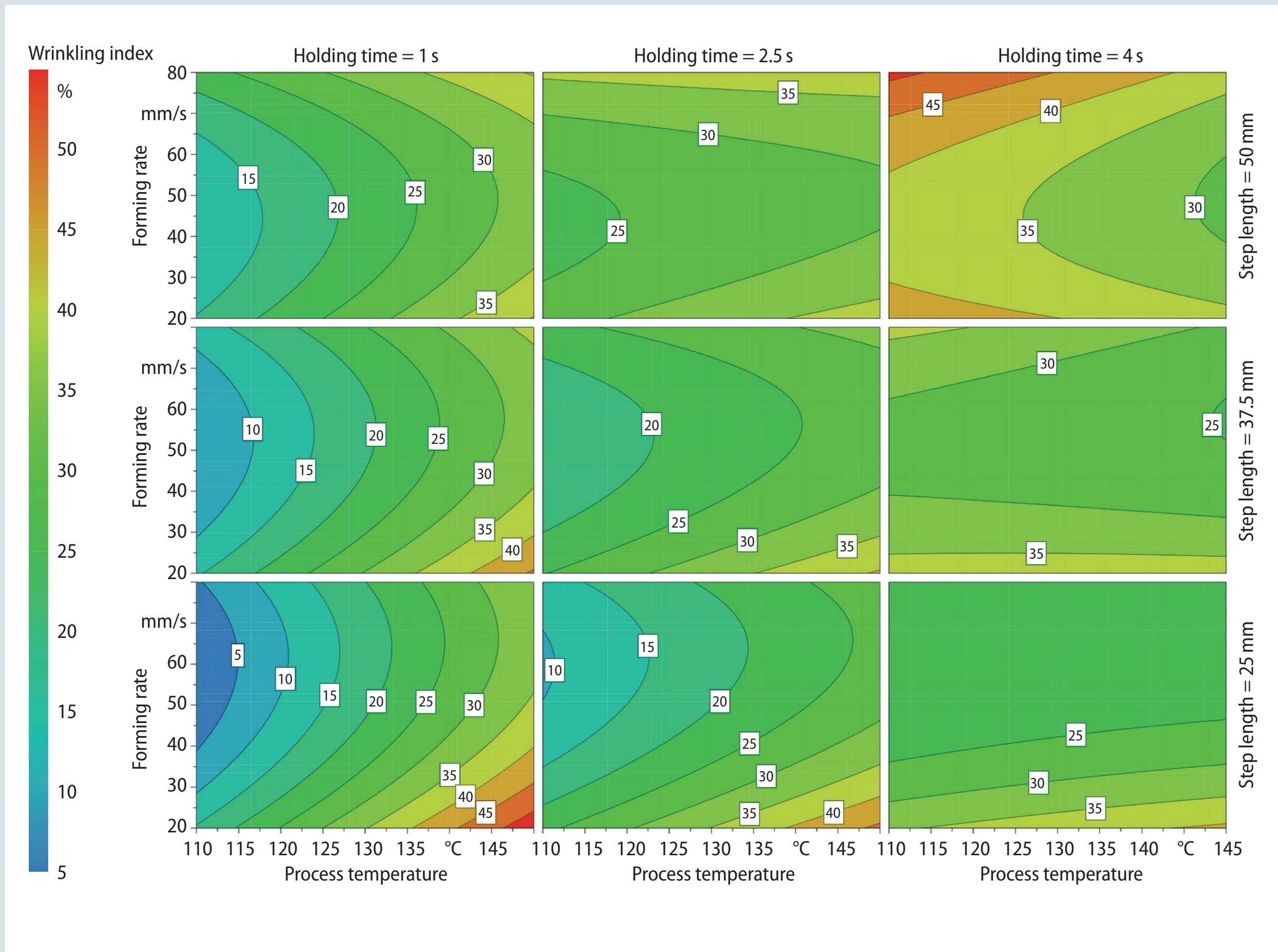

Fig. 3. Contour plot of the DoE study: influence of process parameters on fiber wrinkling Source: Fraunhofer ICT; graphic © Hanser

destructively, the test specimens were photographed under constant lighting from various defined perspectives. The light is reflected differently by wrinkled surfaces than by smooth surfaces. This effect was used to calculate the proportion of wrinkled surfaces in the total surface of the profile using image processing software. The value determined in this way is called the "wrinkling index" and is expressed as a percentage. 0 % corresponds to an ideal wrinkle-free profile, whereas 100 % corresponds to a profile that has wrinkles at every point. In addition to fiber wrinkling, the cross-sectional deformation and the mechanical properties of the test specimens were considered as further quality characteristics.

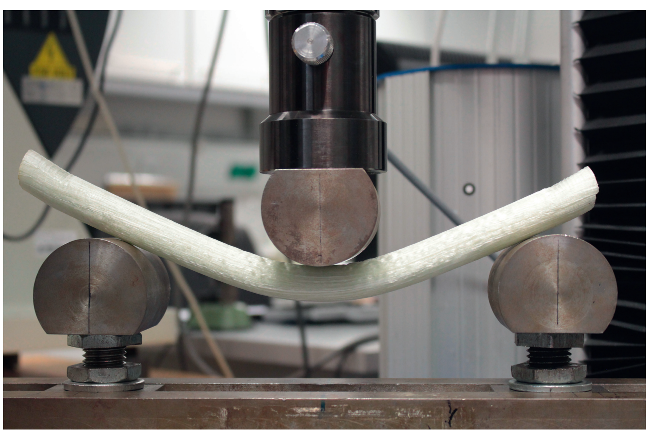

Fig. 4. Test setup for 3-point bending on formed test specimens

© Fraunhofer ICT

The results of the DoE study (**Fig. 3**) provide clear recommendations for minimizing wrinkling with regard to the PETg/GF60 UD tubes investigated here. The optimum process temperature is at the lower end of the recorded temperature range (110–150 °C). In this context, however, it should be noted that, at low process temperatures, some geometric impairments of the test specimens were found. In particular, the internal angle of 130° often cannot be achieved under these conditions because the comparatively high section modulus of a "cool" profile counteracts the forming movement. A good compromise is achieved at about 130 °C. In addition, the reduction of wrinkling is favored by a forming movement consisting of many small steps and short holding times. The lowest wrinkling indices are obtained for the shortest holding time (1 s) and for the smallest step length (25 mm). The latter requires a correspondingly high number of forming steps. Ideally, the forming speed is in the upper mid-range of the measured speed setting, at about 60 mm/s.

The process parameters examined show no significant influence on the cross-sectional deformation of the profile, since this is largely prevented by the core and the mantle.

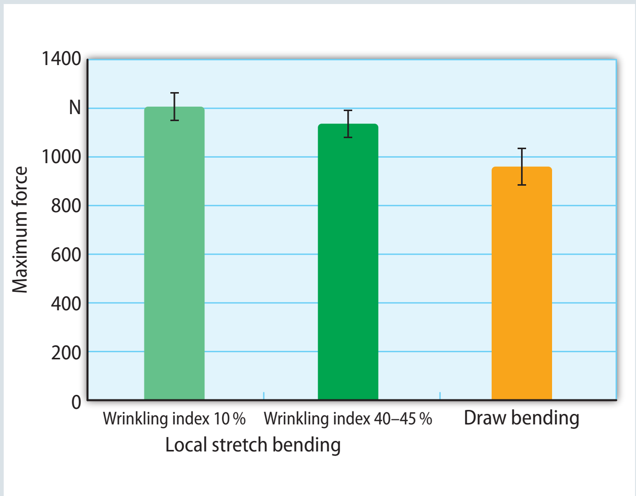

Fig. 5. Measurements from 3-point bending tests: influence of fiber wrinkling on the mechanical properties of formed profiles
Source: Fraunhofer ICT; graphic © Hanser

Mechanical Influence of Fiber Wrinkling

With regard to the mechanical properties of the test specimens, the process parameters are shown to have some influence. For example, the parameter settings that ensure minimal wrinkling also result in the highest mechanical load capacity. Test specimens with a wrinkling index of 40 to 45 % show a 6.1 % lower breaking force in the 3-point bending test (**Fig. 4**) than those with a wrinkling index of 10 %.

The influence of fiber wrinkling on the mechanical properties becomes even clearer when comparing local stretch bending with draw bending, which is well suited for metal tubes. The latter method was used in this study with a commercially available bending form (art. no: 581240, manufacturer: Rems GmbH & Co KG, Waiblingen, Germany). In contrast to the usual method for metal tubes, however, draw-bending was not carried out as a cold forming process, but rather with a process temperature of 130 °C. This process occasionally generates deep wrinkles (**Title figure**) which cannot be observed in local stretch bending. A comparison of the wrinkling index is not meaningful at this point, since it records the distribution of the wrinkles (proportion of the wrinkled surface), but not their depth. Due to these deep wrinkles, the breaking strength of profiles produced by draw bending is 20.5 % lower in 3-point bending than that of test specimens produced by local stretch bending (**Fig. 5**).

Conclusion

Local stretch bending represents a new approach to the local, wrinkle-free forming of thermoplastic UD hollow profiles. In the current state of development, the application range is limited to small forming operations with simple geometric specifications. It is expected that optimizations of the process control and clamping systems as well as adapted material systems will enable the realization of more complex geometries and the processing of solid profiles. ■

The Authors

Jonathan Haas, M.Eng., is a research associate at the Fraunhofer Institute for Chemical Technology (ICT) in Pfinztal, Germany; jonathan.haas@ict.fraunhofer.de
Bernard Bose, B.Sc., is a Master's candidate at the Karlsruhe Institute of Technology (KIT) and has worked as a student assistant at Fraunhofer ICT since 2019 using the described technology.

Acknowledgments
The Unist-HIM project is supported by the Core Industrial Technology Development Program (grant number: 10060281), which is funded by the South Korean Ministry of Trade, Industry and Energy (Motie), through the Korea Evaluation Institute of Industrial Technology (Keit).

Service

Digital Version

- A PDF file of the article can be found at *www.kunststoffe-international.com/2020-10*

German Version

- Read the German version of the article in our magazine *Kunststoffe* or at *www.kunststoffe.de*